THE OPEN UNIVERSITY A SCIENCE FOUNDATION COURSE

UNITS 28–29 GEOLOGICAL TIME AND EARTH HISTORY

STUDY GUIDE

This double Unit consists of five components; the text, two TV programmes and two AV sequences.

Geology is the study of the history of the Earth, and like any other history we cannot understand it until we know *when* events occurred. The main aims of the first half of this double Unit are to explain how geological events can be sorted out and arranged in the order in which they occurred, and how they can be dated. Dating methods vary from simple observations made in the 19th century to the much more accurate quantitative methods of today, based on naturally occurring radioactive isotopes. You will see as you follow the development of dating methods through the Unit how the ordering of geological events through the detailed study of fossil-bearing rocks has been complemented by quantitative age determinations which make use of radioactive isotopes in rocks and minerals. In the TV programme 'Dating a granite', both the ordering of events and the determination of absolute ages are applied to the problem of finding out when a granite was formed. You will find it helpful if you have read as far as the end of Section 5.2 before watching this programme.

The age of the Earth itself is known through absolute age techniques and this sets the stage for a summary of Earth history which dominates the second half of the double Unit, starting with the formation of the Earth and ending with a history of recent climatic changes at the surface. We have highlighted those aspects that can be demonstrated by the fossils in your Experiment Kit and by the colour plates at the end of this binding (which are discussed in the AV sequences 'Introduction to fossils' and 'Fossils as a historical record of life', in Sections 2.5 and 10.7 respectively) and those aspects that remain controversial (and therefore exciting) like the causes of ice ages.

The TV programme 'Frontiers of geology' signposts some directions of active geological research and the nature of questions now being posed by geologists using complex equipment but basic principles from physics, chemistry and biology to unravel the history of our planet.

1 INTRODUCTION

From Units 5 to 8 you already know that all rocks found on the Earth can be divided into three major groups: igneous, sedimentary and metamorphic. In Unit 27 you learned what minerals are found in the common rock types and what the chemical compositions and densities of these rocks are. What other basic data might a geologist require? So far, there has been no mention of how we know the ages of rocks—just how old is each of your specimens in your Experiment Kit, do you suppose?

The granite (S1) is nearly 300 Ma (million years) old, the solid basalt (S3) 60 Ma, and the vesicular basalt (S2) a geological stripling at a mere 10 Ma! But how do we know this? Is it from studying the minerals present, or their chemical composition?

No, the *relative* ages of different rocks that are found exposed near to each other at the Earth's surface can be worked out from the relationships between them as they occur in the field. Geologists can also calculate 'real' ages using the radioactive isotopes present in some rocks, especially in igneous rocks, such as your samples S1 to S5.

The following summary of the stages of the Earth's history has been drawn up from studies of geological time over the past two hundred years. The rest of this double Unit will show how this chronology was worked out.

ERA

STRATIGRAPHIC COLUMN

PERIOD

The whole of geological time is divided into four major divisions called **Eras** (see Table 1). These Eras were defined and given their names from the general character of their fossils long before geologists knew anything about the time-scales involved, at a time when the beginning of the Palaeozoic was thought to correspond roughly to the origin of life. (You will see how far this is from the truth in Section 10.)

TABLE 1 The geological Eras

Era	Meaning of name	Time-span
Cainozoic (sometimes spelled Cenozoic)	recent life	65 Ma ago to present
Mesozoic	middle life	250 to 65 Ma ago
Palaeozoic	ancient life	590 to 250 Ma ago
Precambrian	before the Cambrian	older than 590 Ma

These Eras have been arranged with the *oldest at the bottom* in Table 1 and on the back cover of this binding to form the **Stratigraphic Column*** for the Earth. The Stratigraphic Column is made by stacking up the rocks formed during each geological Era in their correct sequence, always starting with the oldest at the bottom.

As you can see from the Figure on the back cover, the last 590 Ma is further subdivided into eleven **Periods**. These again, as you will see in Section 3, were defined long before any absolute ages were known. Note that the left-hand column in the Figure is to scale and that the Precambrian Era covers nearly 90% of geological time.

The ages and localities of the rocks in the Kit are given in Table 2, from which you will see that you have representative samples from the three most recent Eras.

TABLE 2 Ages and localities of rock specimens in your Experiment Kit

No.	Rock	Locality	Age/Ma
S1	granite	Dartmoor, Devon	280
S2	vesicular basalt	Auvergne, France	10
S3	effusive basalt	Skye, Scotland	60
S4	peridotite	Ivrea, Italy	70
S5	gabbro	Aberdeenshire, Scotland	430
S6	sandstone	Leeds, England	300
S7	limestone	Derbyshire, England	320
S8	phyllite	Kinlochleven, Scotland	400
S9	schist	Loch Ailort, Scotland	450
S10	gneiss	Ivrea, Italy	70

When you have completed this double Unit, you should understand the methods that can be used to show that, for example, your sandstone sample, S6, was formed about 300 Ma ago and belongs to the Carboniferous Period of the Palaeozoic Era.

SAQ 1 (a) The age of the Earth is about 4 600 Ma and the species *Homo sapiens* has been present here for about 100 000 years. Supposing that the age of the Earth corresponds to a 3-hour film, how long before the end of the film did our species appear?

(b) If the history of civilization is taken to be 5 000 years, how long is that before the end of the film?

* We are using initial capitals for Stratigraphic Column when it refers to all the Eras and Periods of Earth history. In any particular region of the Earth, the various strata will form a local stratigraphic column.

SAQ 2 (a) From the information in Table 2, assign each rock specimen in the Kit to its correct Era in the Stratigraphic Column.

(b) From the information in Table 2 and the Figure on the back cover of this binding, assign each rock specimen in the Kit to its correct Period in the Stratigraphic Column.

2 ORDERING EVENTS IN TIME

This Section is concerned with the ways in which past events can be ordered by observation and interpretation. The crucial principle here is that by studying present-day sequences in natural processes it is possible to work out similar sequences in the past. We shall consider just a few examples, starting with the very recent past.

2.1 KEY TO THE PAST

Even before people had any accurate means of measuring time, they knew that there were regular sequences in nature: day follows night, spring follows winter, and sometimes the results of these daily or annual fluctuations are preserved in nature, for example, in annual tree rings.

From what is known of the forces controlling the processes that can now be observed on the Earth's surface, namely the laws of physics and chemistry, there is no evidence that they were any different in the past. It seems reasonable, therefore, to suppose that the present is the key to the past. This commonsense approach to the interpretation of past geological events may seem very obvious today, but it was a revolutionary idea when it was first presented about 150 years ago, as you will see in Section 3.

There is one further implication of the principle that the present is the key to the past: it can also be used in some cases as a key to the future. Some geological events happen on a time-scale that makes their prediction of vital importance to us, earthquakes and volcanoes being the most dramatic examples. In many countries well away from plate boundaries, including Britain, there is little chance of major damage by either of these in the foreseeable future, but on a slightly longer time-scale it is important to know whether a new Ice Age is imminent, a problem which is discussed again towards the end of this double Unit. Occasionally, it is possible to work out a chronology giving actual dates, by counting annual events of the fairly recent past, starting from the present and working back. But, apart from quantitative dating using radioactive elements (radiometric dating) (Section 4), most geological methods do not give absolute ages; they can only be used to work out the *relative* order in which things happened.

2.2 PUTTING THINGS IN ORDER

The ways in which geological events can be ordered in time can best be explained by example and analogy.

Consider first an example from the recent past. Various objects have been found in old refuse dumps near mining camps in North America, and seven examples of these are shown in Figure 1. Their distribution in three boreholes through one dump is shown in Figure 2. The dates of manufacture of the bottles, cans and nails are known from their makers' old records, and so a 'range chart' can be worked out showing the duration of manufacture of each item (Figure 1). You will realize that some of these articles can be used to give a fairly exact age to a part of the dump because they were in use for only a few years, while others were used over a long time and so are not so

FOSSIL

HOMINID

VARVE

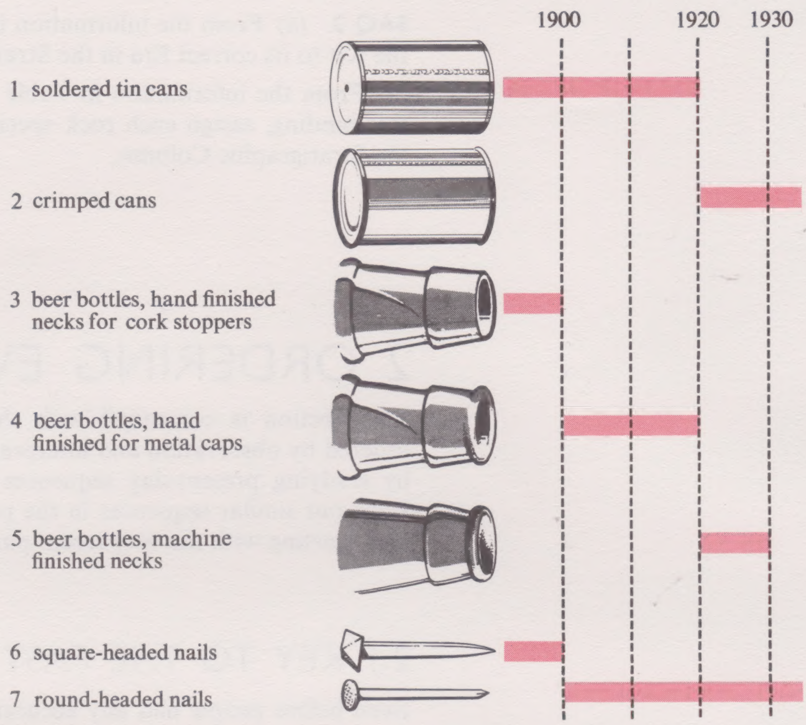
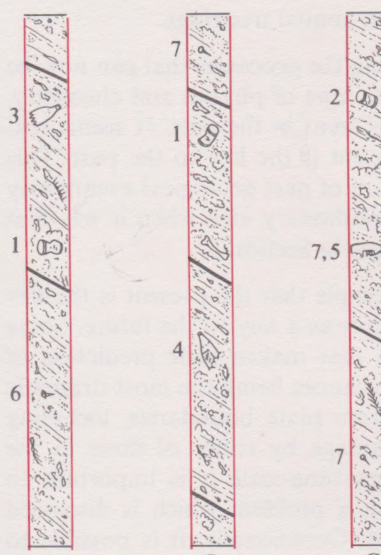


FIGURE 1 Range chart of dates of manufacture of cans, bottles, and nails prepared from historical records. Each article is given a number, and these numbers are used in Figure 2 to show where the articles were found in the boreholes.

valuable for dating. Some groups of articles were only in use together for a very short time, and so an assemblage of these found together can tie down the age of the dump very precisely. (For example, finding items 3 and 4 together would indicate the date of 1900.) Now try ITQ 1.

ITQ 1 With the aid of the 'range chart' in Figure 1, work out the ages of the rubbish in boreholes A, B and C in Figure 2.

In a directly analogous way many sedimentary rocks can be dated by the fossils they contain. **Fossils** can be formed when plant or animal remains become buried in accumulating sediment (such as mud on the floor of a sea or lake) before they are completely decomposed, and as the sediment hardens into rock, the traces of organic material are preserved. Preservation can take a variety of forms: the hard parts of the organism may remain more or less intact, while softer parts may form an impression or cast which is later filled with sediment. Thus, insects completely preserved in every detail in drops of amber (fossilized resin) and the footprints left by a dinosaur on an old land surface can both be described as 'fossils'.



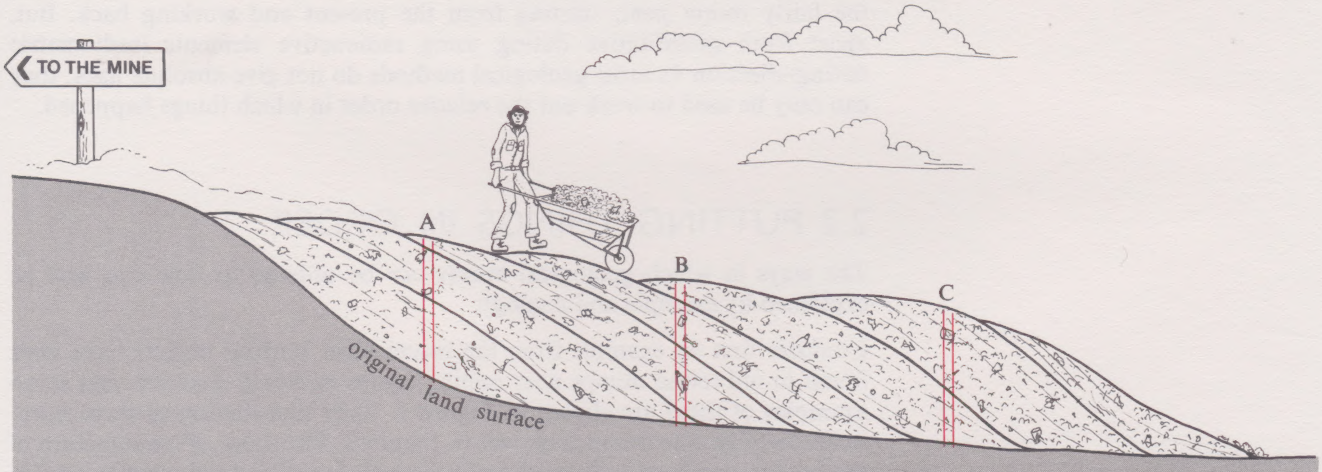


FIGURE 2 Rubbish dump of old American mining camp, to show the distribution of the cans, bottles and nails in the rubbish (stippled) tipped on the original land surface (grey). The rubbish found in 3 boreholes A, B, C (red) is shown enlarged above. The numbers beside the boreholes refer to the articles shown in Figure 1 found at that depth.

The next example goes back a little further in time to consider the tools of our early ancestors, and the ways in which these tools were modified and improved as time went by. **Hominids** (a term including not only *Homo sapiens* but also various extinct species of the genus *Homo*; see Unit 21, Figure 25) appeared on the Earth about 3 Ma ago, and Figure 3 illustrates some of the primitive tools they invented. These tools can be used to date early remains since the sequence in which they were developed is now known, through first the Stone Age, to the Bronze Age and then the Iron Age.

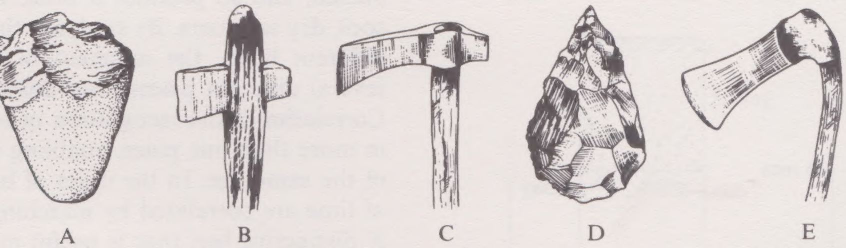


FIGURE 3 Axes made of various materials: A, B, D of stone, E of bronze, and C of iron (for use with ITQ 2).

ITQ 2 Examine the axes in Figure 3 and arrange them in order of decreasing age.

Can you see the assumption behind this method? It is that the tools 'evolved' from stone to bronze to iron everywhere at about the same time (otherwise a stone axe from one area might be the same age as a bronze one from elsewhere). On a broad scale this is probably true, but consider present implements: people in industrialized countries and contemporary primitive tribes are producing very different artefacts for future geologists to discover!

Once you have placed these items in their correct order, you need further information to find out when the tools were used, that is, some *quantitative* method of measuring time is needed.

2.3 VARVES

You may have seen the rings in a cut tree-stump, and you probably know that you can find the age of the tree by counting these annual rings. The oldest living trees are bristlecone pines in California, which have up to 4 900 annual rings! By careful examination of these rings, it is possible to build up a chronology starting from the present. Particularly warm and wet seasons produce thicker than average rings, and cold and dry seasons result in thinner ones. The pattern of past seasons can be 'read' from these distinctive rings, which can be recognized in any tree, and an exact time-scale can be worked out back to the date of the oldest tree.

Geologists were able to establish a similar chronology when they discovered **varves**. These are finely banded sediments, laid down in lakes associated with glacial activity, where each layer represents one year's sediment.

Consider a glaciated region such as Greenland or the Swiss Alps at present. During the spring and summer thaw, sediment consisting chiefly of silt and clay is brought into lakes near a glacier by streams from melting ice. During the winter these streams and the surface of the lakes are frozen and so no sediment is carried into the lakes. The larger silt and sand particles settle to the bottom first, during the spring and summer, but the smaller clay particles settle more slowly and so are not deposited until the autumn and winter when the lake water is still. Thus a single varve (which can be from a few millimetres to a few centimetres thick) is laid down each year, and is composed of silty material at the bottom, gradually grading upwards into finer clay.

GRADED BEDDING

CORRELATION

MARKER HORIZON

Varved sediments, which are shown schematically in Figure 4, are good examples of **graded bedding**, where within an individual unit of sediment the coarser material at the base passes gradually upwards into progressively finer sediment towards the top. There is then an abrupt change to the next varve, which starts again with coarser-grained material brought down by the rush of waters produced by melting the following spring.

Varved sediments are useful to geologists trying to work out details of the past because distinctive layers result from deposition over a period of a few years: a particularly hot summer will give more sediment as more ice is melted, and so produce a thick varve: conversely, thin varves result from cool, dry summers. By studying the pattern of varves in deposits from many different lakes, the sediment of distinctive seasons can be recognized in several different places, thus enabling geologists to correlate the sediments. **Correlation** is the recognition of some past event in the sedimentary record in more than one place, enabling the adjacent sediments to be shown to be of the same age. In the cases of bristlecone pines and varves, short periods of time are correlated by matching records of particularly unusual seasons. A distinctive bed that is useful in correlation from lake to lake is called a **marker horizon**.

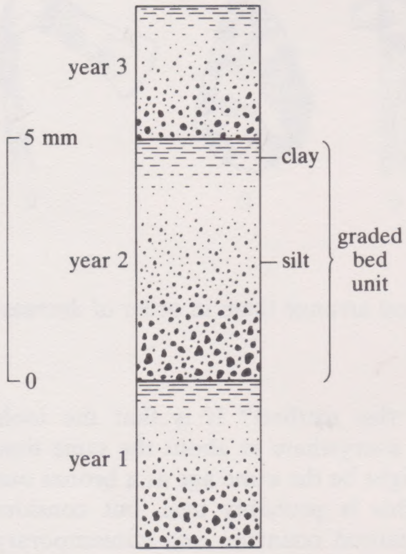


FIGURE 4 Vertical sequence of varves, in which each individual layer represents one year's sediment. This is an example of graded bedding, where there is a *gradual* change upwards from coarser to finer sediment within each annual layer, in contrast to the abrupt change from fine to coarse at the base of each layer.

Varves formed during the Quaternary Period are observed in Scandinavia and eastern North America, and the longest chronology has been worked out in Sweden and Finland, dating events through about the last 12 000 years and correlating the varves from sites as far as 1 000 km apart. To make use of this method, one has in some way to *date* one of the varves, and the best way to do this is to find a lake where varves are still being formed and then to start from this year's varve and count backwards.

Although geologists normally have to work with rock sequences where individual units do not represent annual events, the principle of finding distinctive marker horizons that can be correlated from one place to another is exactly the same. Then, having established the sequence of strata in an area, another method such as radiometric age determination is needed to establish an *actual* age. Varves are interesting but, as they are clearly limited to thousands of years, they are of little use to geologists, most of whom work on a time-scale many orders of magnitude greater. Ideally, we want a chronology that goes back to the beginning of the Earth, thousands of millions of years ago.

2.4 FOSSILS AND EVOLUTION

In a directly analogous way to the dating of the mine dumps discussed in Section 2.2, many sedimentary rocks can be dated by the fossils they contain. Several early philosophers such as the Greek, Herodotus, correctly deduced as early as the 4th century BC that fossils now found in sedimentary rocks were the remains of ancient sea creatures. He went on to reason that the rocks in which these fossils were found must have been laid down in the sea. However, along with many other perceptive ideas of the ancient Greeks, this theory became lost for the next 2 000 years, overshadowed by prevailing religious beliefs. Even as recently as the 17th century, some scholars thought that the Earth was only 6 000 years old, and that fossils were the remnants of Noah's Flood or the work of the Devil, who had deliberately placed fossils in rocks 'to deceive, mislead or perplex mankind'.

Before considering how fossils can be used by geologists, it is best to have a careful look yourself at the fossils in the Kit to 'get your eye in'.

TERMS IN AV SEQUENCE
AMMONITE
BIVALVE
BRACHIOPOD
CORAL
CRINOID
ECHINOID
DINOSAUR
TRILOBITE

2.5 INTRODUCTION TO FOSSILS (AV SEQUENCE)

For this sequence you will need the tray of fossils and the hand lens from your Kit, and the Colour Plates at the end of this binding. This AV sequence (on Tape 4, Side 2, Band 2) should take about half an hour.

The main purpose of this AV sequence is for you to have a first look at the fossils in your Kit so that you can begin to recognize the major groups of fossil animals which they represent, and to complete Table 3, using the information on the tape and the Stratigraphic Column on the back cover. It is *not* necessary for you to learn all the genus names of these animals, or their ages, but you should remember the groups to which they belong.

All the 'fossils' in your Kit are casts prepared from moulds taken from particularly fine museum specimens, which have been extracted from the surrounding rock by careful preparation. This enables us to give you all identical specimens, and does not involve us in spoiling good localities by trying to collect 7 000 samples. Such perfect specimens are very rarely found in the field. In the text, these fossils will often be referred to by their letters, which have been chosen to remind you of the names of the group to which each belongs. As you listen to the tape, fill in the spaces in Table 3: you should record the correct name of the group to which each fossil belongs, the common name if any, and the geological Period and age in Ma.

Please do not write on or mark the specimens

TABLE 3 Experiment Kit fossils (for use with AV sequence)

Letter	Group name	Common name	Genus	Locality	Geological Period	Age/Ma
G	....	....	*Neptunea*	Essex	....	....
F	....	....	*Diplomystus*	Wyoming, USA	....	....
E	....	....	*Phymosoma*	Kent	....	....
L	....	....	*Cererithyris*	Somerset	....	....
B	....	....	*Cucullaea*	Dorset	....	....
A	....	....	*Quenstedtoceras*	Dorset	....	....
D	....	....	*Albertosaurus*	Alberta, Canada	....	....
R	....	....	*Cheirotherium*	Merseyside	....	....
T	....	....	*Calymene*	Worcestershire	....	....
S	....	....	*Gissocrinus*	Worcestershire	....	....
C	....	....	*Lithostrotion*	Avon	....	....

When you have listened to the tape, have a go at identifying a few drawings of various invertebrates by attempting ITQ 3. Some of these are very easy, others are deliberately a bit tougher. (You should work carefully through the answers, making a few notes on or below Figure 5 as you go.)

ITQ 3 Identify the group to which each animal in Figure 5 belongs, and write the name in the spaces provided beside or below each animal.

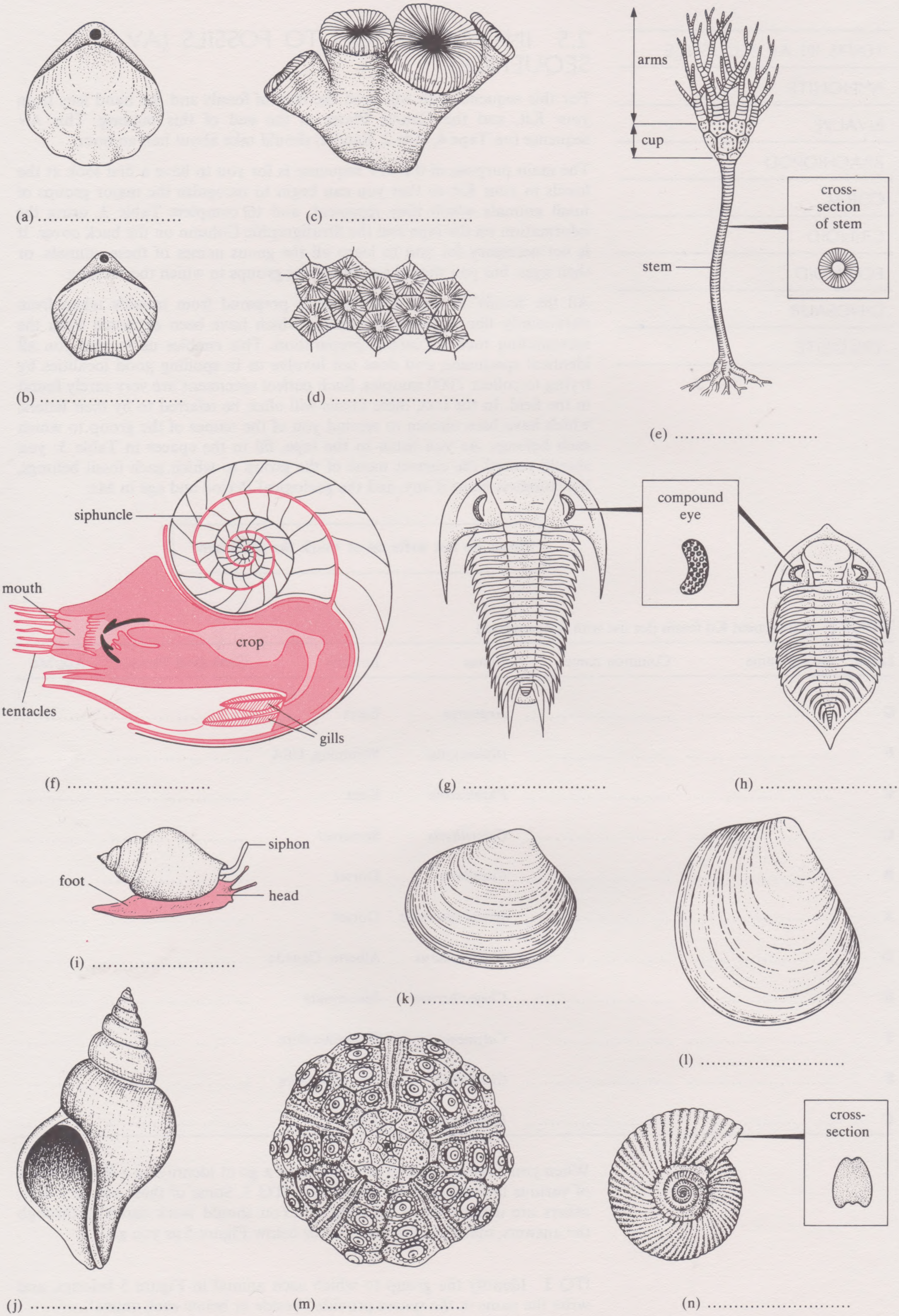


FIGURE 5 Selected invertebrate fossils for ITQ 3. Note soft parts are shown in the cross-section of the animal in (f) and in the sketch of the whole animal in (i). Animals are shown approximately natural size.

PALAEOECOLOGY

STRATA

STRATIGRAPHIC SEQUENCE

We shall return later to the major changes that have taken place in the invertebrate population of the Earth, but you may have already realized that some of the major fossil groups such as the trilobites have no living descendants today, that is their line is extinct; others, however, such as the bivalves, are extremely well represented today around Britain's shores. When we can find a good assemblages of fossils preserved together in a sedimentary rock it is possible to work out the sort of 'fossil community' of animals that lived together at that time, and even to establish how they interacted with each other; in other words to study the ecology of the past, or **palaeoecology**. As you might expect from studying Unit 25, we can recognize grazers living on vegetation, scavengers, filter feeders and predators, and even in some very fine-grained rocks the remains of plankton at the bottom of the food chain. And in all these ecological niches different invertebrate groups have tended to be dominant at different stages of Earth history. But for the moment we must return to the use of fossils in establishing the relative ages of particular sedimentary rock units or **strata**.

Fossils are now widely used to determine the relative ages of rocks, and so place them in their correct order, that is, their correct **stratigraphic sequence**. But how was this sequence originally worked out? As you will see in Section 3.3, William Smith and Georges Cuvier discovered that *overall* there is a sequential order of fossils through time; the biological explanation of this came later, particularly with the work on evolution by Charles Darwin (1809–1882).

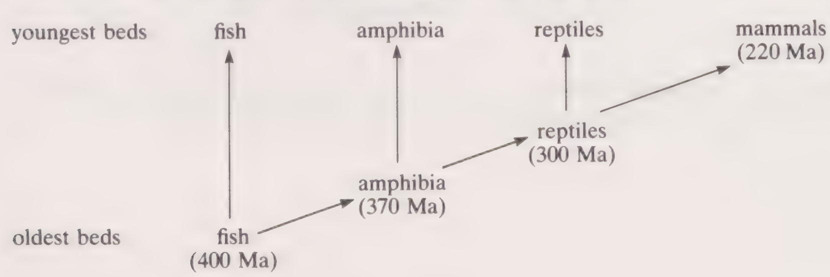
Much of the general course of evolution can be verified by the study of fossils. By careful collection, palaeontologists have discovered a discontinuous record of fossils in the Stratigraphic Column from the end of the Precambrian to the present. The stratigraphic sequence of the rocks was established first by mapping them in the field and, from the relationships of rock strata to each other, deciding on their relative ages. Having done this, it was then possible to work out the sequence in which fossils appeared through geological time. Once this sequence of fossils had been established, the fossils themselves could then be used to date other rocks.

The fossil record is not complete, as you can imagine, because very few of the animals and plants living at any one time are preserved as fossils. For example, very few specimens of hominids have been discovered. Because they lived on land, their chances of being preserved in sediments were much less than those of animals that lived in the ocean. Some marine organisms are fairly abundant in the rocks in which they are found and the evolution of individual species can be traced in greater detail. Sometimes a particular species is only found through a few metres of rock in one Period, with its ancestors below, and its descendants above. In such cases a single fossil can pinpoint very accurately in the Stratigraphic Column the rock in which it is found.

Fossils can now be used to determine the relative ages of rocks back to about 600 Ma before the present, at which time abundant shelly fossils first appear in sedimentary rocks. The evolutionary order of animals and plants can be used to establish the relative ages of rocks because we assume that, in general terms, evolution proceeds from simpler to more complex organisms; for example, the evolution of the vertebrates followed the sequence:

fish ⟶ amphibia ⟶ reptiles ⟶ mammals

If we place this sequence in stratigraphic order we have:



RELATIVE DATING METHOD

Before the Devonian Period the only vertebrates were fish; by about the Cretaceous all four groups had evolved.

Thus the oldest rocks in this sequence will contain only fossil fish and the youngest, besides containing mammals, will also yield fossils of all four groups which have evolved from the common ancestor, the fish. The detailed evolution of the vertebrates, to which all these animals belong, is much more complicated than this (Figure 6). For example, during the Jurassic and Cretaceous Periods (the age of the dinosaurs), fish, amphibia, dinosaurs and other reptiles existed, but mammals and birds were barely significant.

When the relative ages of strata from different localities have been established by the sequence of the fossils they contain, the rocks can be arranged into a Stratigraphic Column, but no actual ages can be given to rocks by the use of fossils alone; it is therefore only a **relative dating method**.

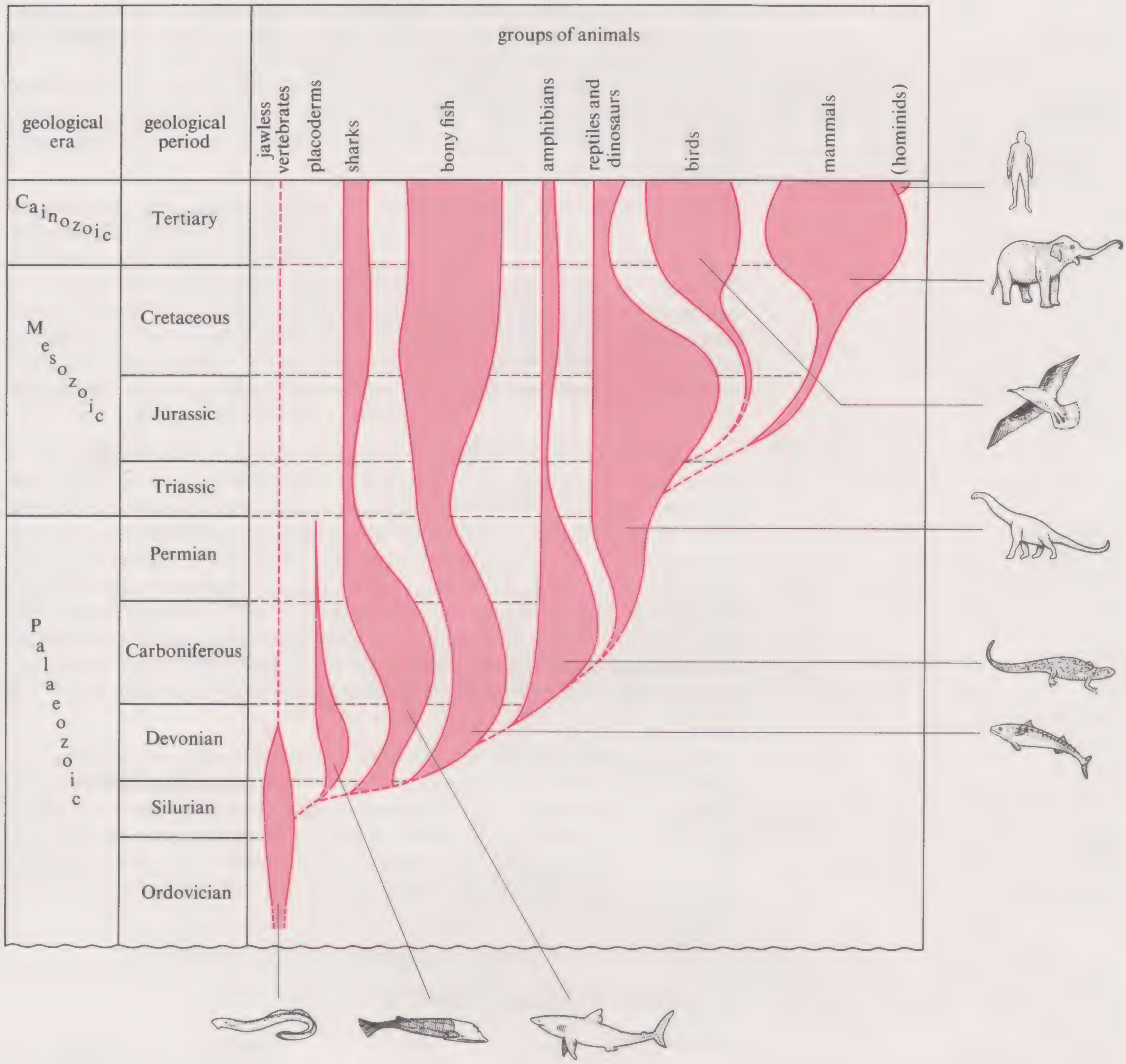


FIGURE 6 Geological range of the vertebrates showing when the various groups of animals evolved from each other. The width of each group indicates the approximate number of species living at that time.

SUMMARY OF SECTION 2

This Section has provided examples of how events can be placed in chronological order by detailed observations, principally by the use of fossils.

1 The kinds of fossils found in a sediment tell us whether that sediment was formed before or after other sediments containing different fossils *provided* that the fossils can be placed in an evolutionary sequence.

2 By studying the details of fossil remains, it is often possible to work out how a particular organism lived, and, where an association of several organisms is found together, even to work out something of the ecology of the past.

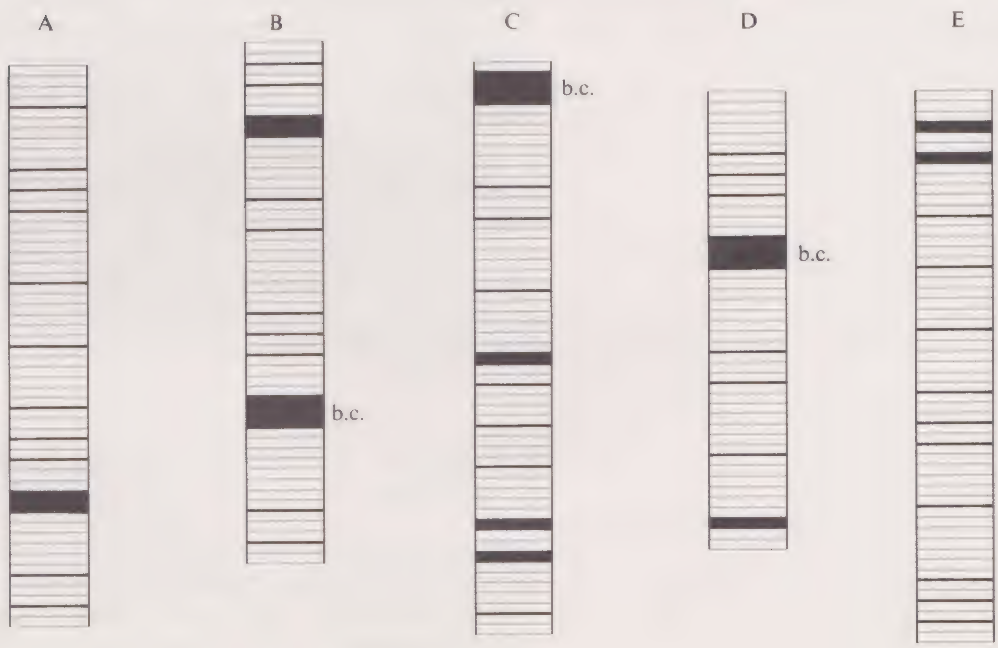
3 Many sedimentary rocks do not contain fossils and it is often useful to use distinctive rock types (marker horizons) to correlate sediments from one area to another.

4 Combining the theory of evolution with painstaking observations on fossils and marker horizons, a stratigraphic sequence can be built up which defines the age of any one sediment in the sequence relative to all the others.

SAQ 3 Explain how graded bedding in varved sediments can be used to interpret varves as annual layers of sediments deposited in glacial lakes which become frozen over each winter.

SAQ 4 Figure 7 shows a series of measured sections of varved sediments in boreholes from different glacial lakes. Each black line in the diagram represents the coarse fraction of a year's sediment (the layer of silt), the white layer above being the fine sediment deposited in the winter. In many years, due to a longer summer season, a thicker layer of coarse sediment was laid down. Several exceptional seasons are characterized by an abundance of organic material and are shown as black layers more than 1 mm thick. (These years have no white layer in the diagram.) One such layer (labelled b.c.) contains distinctive, brown, lake clay and appears in several of these sections, thus providing a useful marker horizon.

(a) Correlate these sections by matching the distinctive beds.
(b) Draw up your own stratigraphic column for this sequence of beds.
(c) In which borehole are the oldest beds?
(d) How many years are represented by this stratigraphic column?



b.c. is a distinctive layer of brown clay
other thick varves are also shown

FIGURE 7 For use with SAQ 4. Measured sections of varved clays from five glacial lakes. Each black line represents the coarse fraction of one year's sediment laid down in the summer, the white layer above being the finer sediment laid down during the winter. A few exceptional years are represented by very thick black beds, where an abundance of organic material colours the whole year's sediment. (These years have no white layer on the diagram.) The thickest layer of all (labelled b.c.) forms a distinctive marker horizon, containing abundant brown clay.

PRINCIPLE OF SUPERPOSITION

SAQ 5 To which of the fossils in your Experiment Kit are the following most closely related, and therefore, in which group would you place them?

(a) Edible oyster (b) Garden snail (c) Edible clam (d) Periwinkle (e) Starfish

3 HOW THE STRATIGRAPHIC COLUMN WAS DEVELOPED

This Section describes some of the key discoveries, mostly made in the 19th century, that enabled the Stratigraphic Column for the Earth to be worked out. From the principles of superposition of rock strata (oldest beds at the bottom), faunal succession (the regular sequence of fossils with time), and uniformitarianism (the present is the key to the past), combined with mapping of rocks in the field, arose a picture of a gradually evolving Earth, which was in contrast to the earlier catastrophic theories of Earth history. All this was long before any actual dates could be assigned to past geological events. This Section is concerned entirely with working out *relative* ages, and is fairly straightforward.

3.1 SUPERPOSITION

The first attempt to recognize a sequence of historical events in sedimentary strata was made by a Dane, Nicolaus Steno (1638–1687) in the mountains of western Italy. He recognized that older rocks are overlain by younger rocks, which is the **principle of superposition**. Steno also realized that strata that are normally deposited slowly (like varves) are laid down in a near-horizontal position, although later they may be folded and even overturned.

There are often features present within a sedimentary rock that geologists can use to interpret which way up the sediment was when it was laid down; you have already met one such feature, graded bedding, in the varved sediments. Look again at Figure 4. Can you see how, if you could recognize graded bedding, you would always be able to tell the original bottom and top of such a sequence of strata? (Try looking at the Figure upside down.)

The coarser material is always at the *base* of a unit, passing *gradually* to a finer-grained top. If subsequent Earth movement should fold or even invert these rocks, the original orientation would be clear. There are many other similar features that geologists can use to tell the original orientation of sediments.

If we examine a series of sedimentary beds in the field and can determine from some feature such as graded bedding that they are the right way up, then a stratigraphic column for these beds can be prepared using the principle of superposition: the oldest beds will always be at the bottom, overlain by younger beds. You can see this clearly in Figure 2 with the 'beds' of the mine dump. Younger rubbish overlies old rubbish, although the 'beds' here were not laid down exactly horizontally!

3.2 FIRST ATTEMPT AT A STRATIGRAPHIC COLUMN

An Italian, Giovanni Arduino (1713–1795), prepared a simple stratigraphic column for the rocks of northern Italy. Having studied how individual rock strata were related to each other where he saw them exposed in the field, and having looked at the character of the rocks themselves, he split his column into three:

Tertiary soft limestone with fossils, clay and sandstones;
Secondary hard limestones and mudrocks with fossils;
Primary severely folded metamorphic and igneous rocks without fossils.

If you examine the modern Stratigraphic Column on the back cover, only the term 'Tertiary' has survived from this first classification (as a Period name within the Cainozoic Era). Arduino's 'Secondary' very roughly corresponds to the present Mesozoic and Palaeozoic Eras combined, and his 'Primary' is roughly equivalent to the present 'Precambrian' Era. This was a beginning, but there was no certainty that these three divisions could be applied elsewhere, because there were no clearly expressed criteria to separate them, particularly the upper two divisions. There was no reason to suppose that rocks of similar age elsewhere would look the same as these strata in Italy.

3.3 FAUNAL SUCCESSION

A Frenchman, Georges Cuvier (1769–1832) was one of the first to describe systematically the skeletal remains found preserved in rocks as fossils, to interpret them in terms of the living organisms they represented, and to work out their succession in Earth history. He studied the fossil plants and animals in the Tertiary rocks of the Paris Basin, and concluded that older fossils differed more from living creatures than did younger ones. He summarized his conclusions diagrammatically by sequences of strata, such as those shown in Figure 8. He deduced from these that some older forms of life had become extinct and that the extinct forms had been replaced by newer forms.

But some of Cuvier's conclusions were not correct. For example, in his answer to the question of how new species arose, Cuvier believed that each

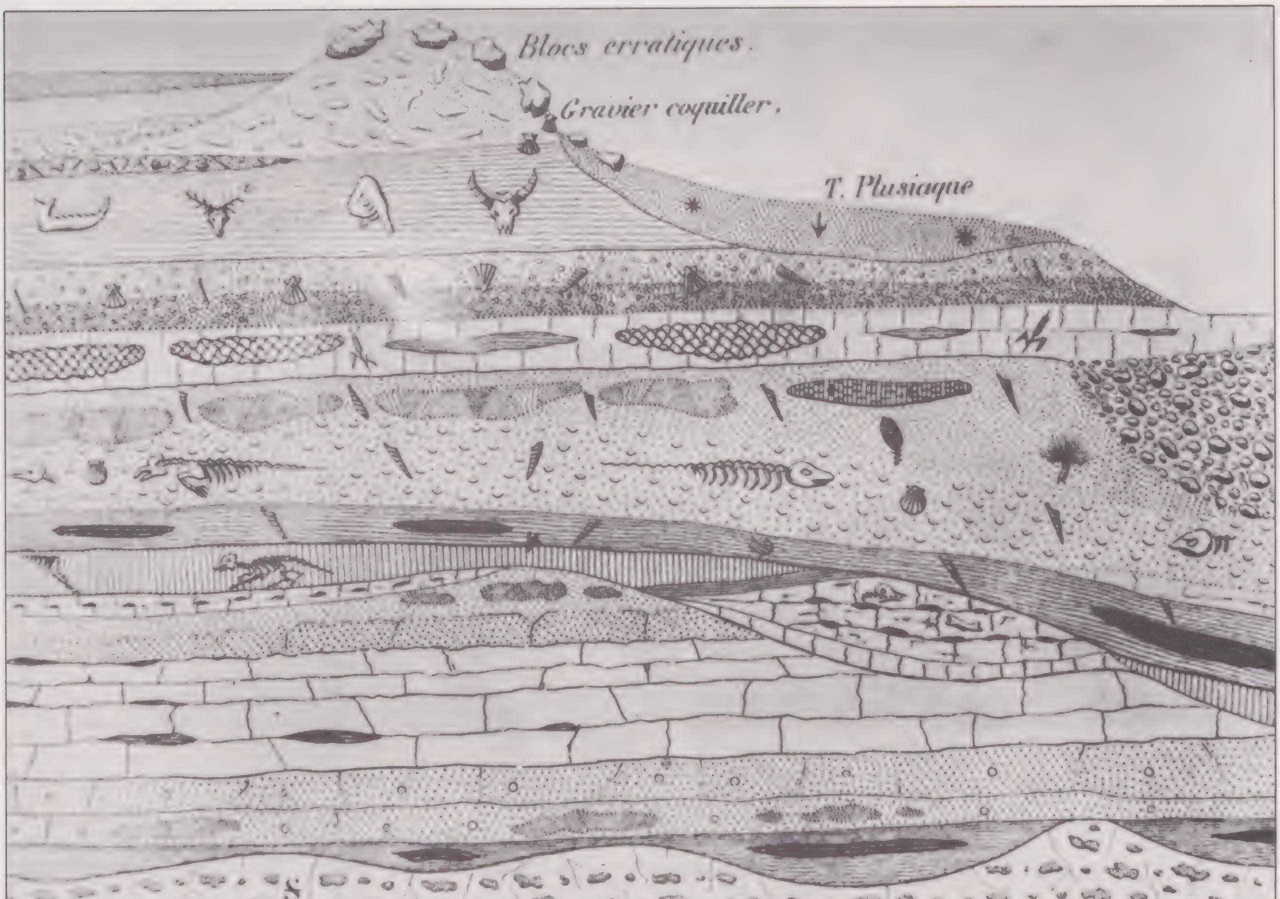


FIGURE 8 Diagrammatic section of strata (after Cuvier), showing how particular fossils are associated with particular horizons in the sequence of strata. Breaks in the sequence where erosion of the underlying beds has occurred before subsequent beds were laid down can be seen in several places, perhaps best where strata with a walking vertebrate (shown by vertical ruling) are overlaid by a horizontally shaded bed.

CATASTROPHISM

UNCONFORMITY

old species was wiped out by a universal catastrophe followed by the 'special creation' of new species.

Catastrophism is the name given to the hypothesis that geological history can be explained by a series of catastrophic events. Starting from the biblical idea of Noah's Flood, Cuvier invoked similar 'deluges' to explain each break in the series of fossils in his sequence of sediments. Since he was not able to find intermediate species connecting the fossils at different levels in the Stratigraphic Column, and since, moreover, there was often evidence of a break in the deposition of the sediments themselves, marked by changes in rock type that coincided with the faunal changes, it was logical to invoke a new 'deluge' for each break. Geological history then was thought to be a whole series of deluges which killed off all life, each followed by special creation of a whole new fauna. During the 19th century there were many graphic representations of 'deluges', one of which is shown in Figure 9.

FIGURE 9 The Asiatic Deluge, from Louis Figuier (1869) *The World before the Deluge.*

Cuvier noticed that very often the breaks in the sequences of strata and fossils were marked by a horizon where there was evidence of erosion of the underlying beds before deposition of the next layer, and that the beds immediately above contained pebbles. Indeed this was powerful evidence for the 'deluge'. Such breaks in the Stratigraphic Column often do represent a long interval of time, during which sedimentation ceased and erosion occurred because the area had risen above sea-level, They are important features of the Stratigraphic Column, and are known as **unconformities**. Several unconformities are shown in Figure 8. The stages in the formation of an unconformity are shown in Figure 10. The pebble bed that marks the time when the area sank beneath the sea, and sedimentation began again is in effect a 'fossil beach' formed as the sea gradually 'drowned' the land. Recognition of unconformities, and the missing strata they may represent, is crucial in working out the geological history of an area.

ITQ 4 How many Ma are represented by the unconformity in Figure 11?

In the last years of the 18th century an Englishman, William Smith (1769–1839), an engineer and surveyor, who worked on canals, roads and drainage schemes all over England, found that he could recognize distinctive beds within rocks such as the chalk on the North and South Downs, or within the coal-bearing strata in widely separated coalfields, and that *each group contained a particular assemblage of fossils quite distinctive from those of the strata above and below.*

He began to correlate apparently dissimilar sedimentary strata *because they contained similar fossils.* Furthermore he found that there was the *same suc-*

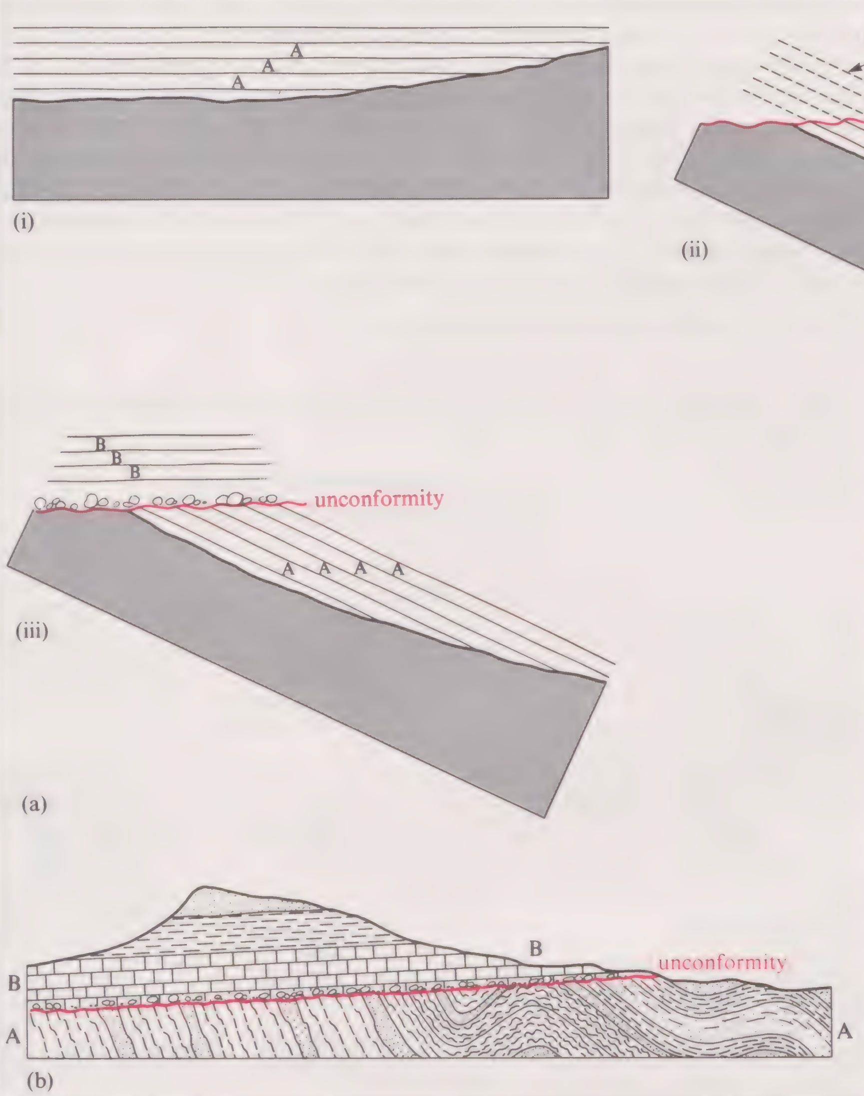


FIGURE 10 Unconformities. (a) Stages in the formation of an unconformity (as seen in cross-section). (i) Sediments A are laid down under water on pre-existing rocks (grey tone). (ii) The area is tilted, lifted above sea-level, and some of the original sediment eroded away. (iii) The area sinks beneath the sea and a second series of sediments, B, are laid down on the old erosion surface. A layer of pebbles represents a fossil beach on the old erosion surface, which is now called an unconformity. (b) Cross-section of a typical unconformity (simplified) which occurs in the Ingleton area. The time interval represented by the unconformity can be many tens or hundreds of Ma. In this case the older strata, A, were folded and eroded before the younger strata B were laid down. Since strata B were deposited there has only been slight tilting and uplift, and erosion to form the present land surface.

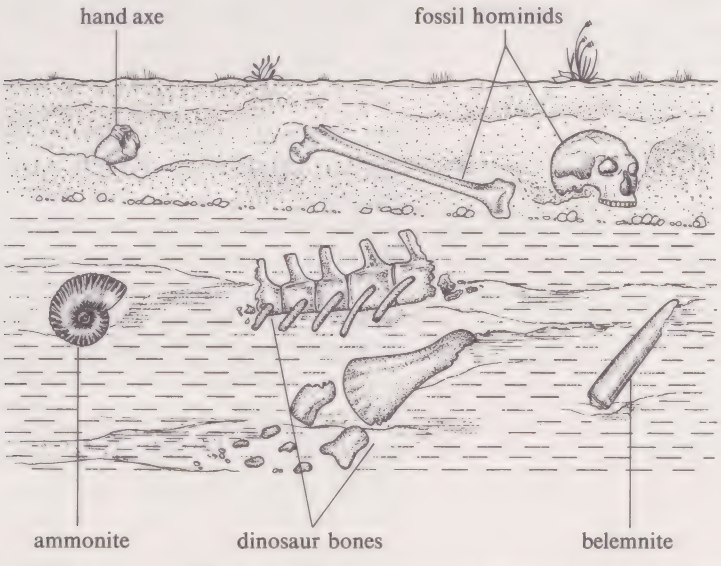


FIGURE 11 Hypothetical unconformity (for use with ITQ 4). The fossils in the lower bed became extinct at the end of the Cretaceous, long before hominids appeared.

PRINCIPLE OF FAUNAL SUCCESSION

OUTCROP

cession of fossil assemblages from older to younger beds in all parts of the country. He concluded that each stage of this succession of fossils represented a particular span of geological history, or a discrete period of time, and that rocks formed during that time would contain the same fossils wherever they occurred geographically. This he called the **principle of faunal succession**, and, using it, he was able to correlate widely separated outcrops of rock by the fossils they contained. An **outcrop** of rock is a piece of the solid rock strata which is visible at the surface, so it 'crops out' through the soil and vegetation cover. An outcrop does not include stones or boulders that have become detached from the rock units they represent.

Now try a similar correlation exercise for yourself.

ITQ 5 Figure 12 shows two columns of rock from well-separated localities A and B, with their fossils sketched in.

(a) Draw lines of correlation across linking the two columns.
(b) Suggest where there may be unconformities in column A.

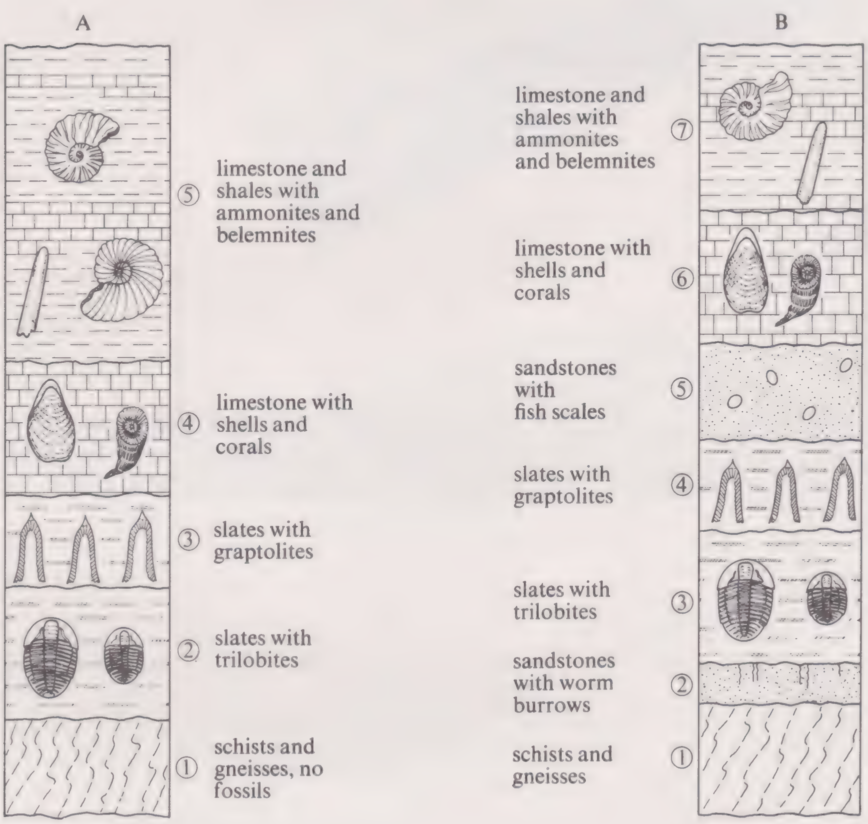


FIGURE 12 Columns of rock strata from two localities A and B with their fossils (for use with ITQ 5).

By using this method of correlation and applying the hypothesis that each faunal assemblage really represented a unique time interval that could be recognized anywhere, Smith was able to produce in 1815 the first geological map of England and Wales and part of Scotland. On a scale of five miles to the inch, it measured about 2 m by 3 m. He took an existing geographic map and showed the outcrops of each stratum by painting them in water colours. (Painting the geology onto a geographic base remained the main method of producing geological maps for more than a hundred years until it was superseded by colour printing.)

Having produced the map, Smith was then able to draw a geological section across it along the road from London to Snowdon, to show the relationship between the different strata. A simplified version of his 1817 section is shown as Figure 13 (page 20).

If you look at Figure 13 you can see that a journey from London to North Wales would take you onto progressively older rocks. You can also see that each range of hills is caused by a particular geological stratum that is more

resistant to erosion than the softer rocks forming the lowlands between. For example, the journey from London to Oxford starts and finishes on soft clays, the high ground of the North Downs and Chilterns between being caused by the harder Chalk.

Now that you have looked at the section, you can appreciate how Smith was able to produce the first nearly complete stratigraphic column for Britain, which accompanied his large map. We have reproduced a simplified version of this as Figure 14. Many of the terms he coined for rock strata are still in use today, although some have been modified, as you will find when you examine the modern Stratigraphic Column for southern Britain in Figure 15.

ITQ 6 Compare Smith's column, which has only the rock strata but no indication of the time-scale involved, with the modern one (Figures 14 and 15) and with the generalized Stratigraphic Column (back cover). How much of geological history did Smith have essentially complete in his column?

3.4 UNIFORMITARIANISM

James Hutton (1726–1797) contributed a great deal to the unravelling of the Earth's geological history, and his work dealt a blow to the religious ideas of great catastrophes as an explanation of the Earth's history. A remarkably perceptive observer of rocks in the field (Figure 16), Hutton thought that he recognized in the rocks of his native Scotland the results of processes taking place on the Earth's surface at present: processes such as erosion, volcanic activity and changes in climate.

Let us look at these processes in turn.

Erosion of land is a continuous process, and the broken-down fragments of rocks are transported to the sea where they eventually become sedimentary rocks. By looking at places where sediments are forming today, it is possible to interpret how old sedimentary rocks were formed. The removal of sediment from the land and its deposition in the sea is a process that can be measured. For example, it is possible to determine how much sediment per year is carried by major rivers. So, by looking at present-day sedimentary deposition, geologists can begin to estimate how long it must have taken for similar sediments to form in the past.

FIGURE 16 James Hutton 'rather astonished at the shapes which his favourite rocks have suddenly taken'. (Caricature by John Kay, 1787. From the block in the possession of the Edinburgh Geological Society.)

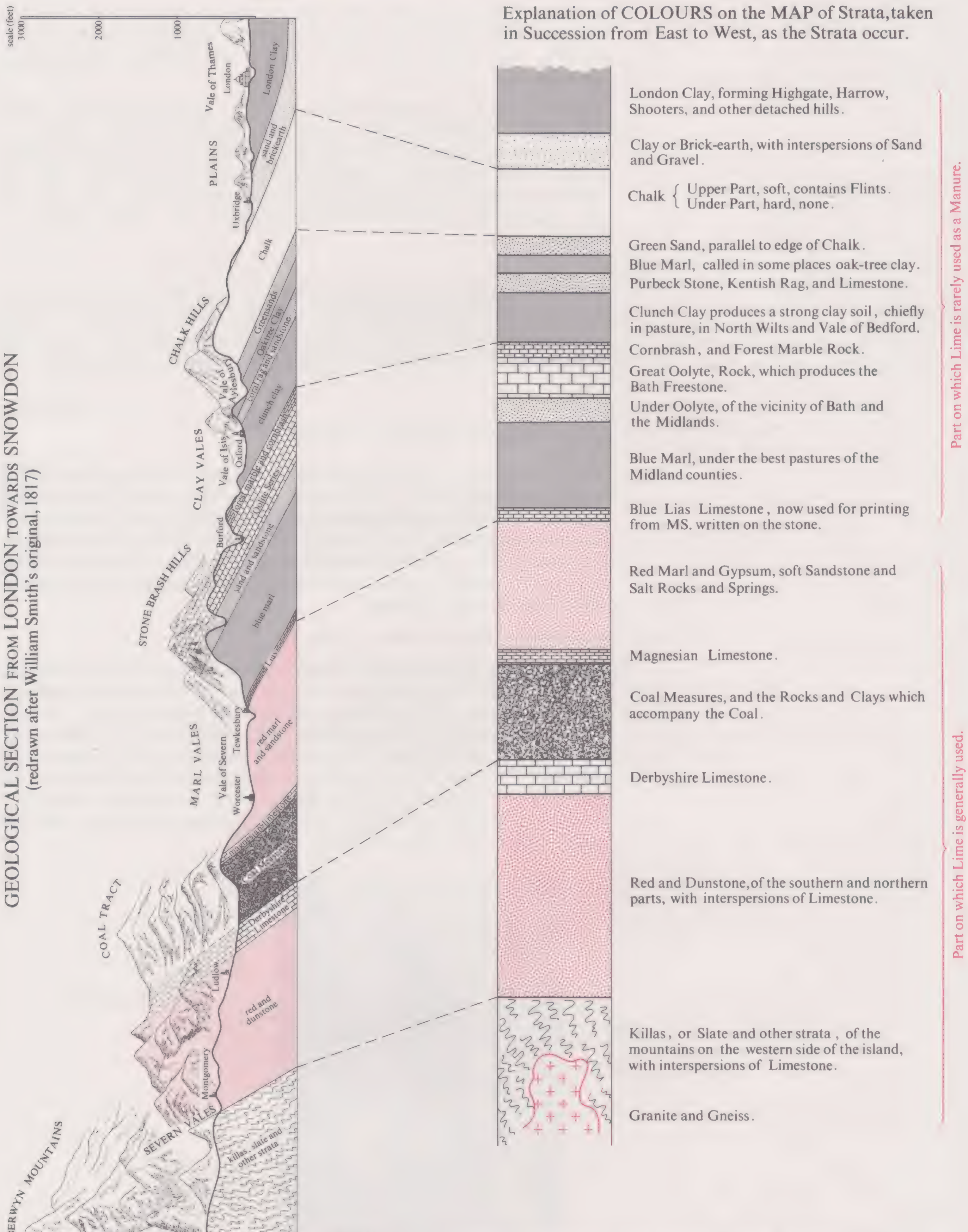


FIGURE 13 Geological cross-section from London towards Snowdon. This section has been redrawn and simplified, the original hand-painted colours being replaced as well as possible by two-colour printing. The solid line represents the road surface, whose gradients appear much steeper here than they actually are because of the enormously exaggerated vertical scale which Smith used (see the right-hand side of the Figure). The succession of strata is accurately shown below the road. Above the road Smith gave an indication of the size of adjacent hills and of the rocks of which they were formed.

Septarium, from which Parker's Roman cement is made.

No building Stone in all this extensive district, but abundance of materials which make the best bricks and tiles in the island.

Flints, the best road materials.
Good Lime for water cements.

Firestone, and other soft Stone, sometimes used for building.

Thin beds, used for rough Paving, makes tolerable roads.

The finest building Stone in the island for Gothic and other architecture which requires nice workmanship.

Small quantities of Copper and Lead.

Grind-stones, Mill-stones, Paving-stone, Iron-stone and Fire-clay from the Coal Districts.

Lead, Copper, and Lapis Calaminaris – Marble.

Some good building Stone.

The Limestone polished for Marble.
Tin, Copper, Lead, and other minerals.

The finest building Stone in the island for bridges and other heavy work.

FIGURE 14 Stratigraphic column drawn up by William Smith (simplified after his original column, which accompanied his 1815 map). The ornaments used here have been changed from his original colours in the same way as in Figure 13. The column consists of the sequence of rock strata that Smith recognized from his field work, with observations about their character, uses, and effect on the landscape.

ERA	PERIOD	Ma ago	ROCK STRATA
CAINOZOIC	QUATERNARY: Pleistocene		glacial materials
		2	
	TERTIARY: Oligocene and Pliocene		sands
		38	
	TERTIARY: Eocene		Bagshot Beds London Clay sands
		65	
MESOZOIC	Cretaceous		Chalk Greensands Weald Clay Hastings Beds
		145	
	Jurassic		Purbeck Beds Portland Beds Kimmeridge Clay Corallian Oxford Clay Cornbrash Oolite Series Lias
		215	
	Triassic		sand and marl
		250	
PALAEOZOIC	Permian		marl and limestone
		285	
	Carboniferous		Barren Measures Productive Coal Measures Millstone Grit Carboniferous Limestone
		360	
	Devonian		Upper Old Red Sandstone Middle Devonian Limestone Lower Old Red Sandstone
		410	
	Silurian		limestones and shales
		440	
	Ordovician		shales and volcanics
		505	
	Cambrian		slates and sandstones
		590	
PRECAMBRIAN	Precambrian		slates, metamorphic and igneous rock

FIGURE 15 Modern Stratigraphic Column for England and Wales. Geological time is shown in Eras and Periods, and the modern dates assigned to these are indicated in red. To the right are the modern names for the rock strata that can be recognized in the field.

PRINCIPLE OF UNIFORMITARIANISM

Volcanic activity Every day there is a volcano erupting somewhere on Earth, so it is possible to study volcanic processes and how volcanic rocks are forming today. This knowledge can then be used to interpret volcanic rocks such as those formed in north-west Scotland 60 Ma ago (like your Kit sample S3) or still older ones, formed about 400 Ma ago in the English Lake District.

Figure 17 shows an example of such a comparison for two pillow lavas (which form when basalt magma is erupted on the ocean floor, usually at a constructive plate margin, see Units 7–8). The pillows in Figure 17a formed on the floor of the Atlantic in Iceland (which you saw in the TV programme 'Volcanic Iceland', associated with Units 7–8), are less than a million years old, and identical pillows have been filmed recently as they formed from eruptions off Hawaii. The similar form of the pillows in Figure 17b enables us to be sure that they too were erupted on the sea floor, though they were formed about 85 Ma ago in Oman.


(a)


(b)

FIGURE 17 Pillow lavas from widely separated localities and ages, both formed in the same way, by basalt lavas being erupted under the sea. (a) Cross-section through lavas, less than 1 Ma old, from Iceland, showing internal structure of individual pillows. (b) Ancient lavas, about 85 Ma old, from Oman, showing general form of whole pillows.

Changes in climate From studies of erosion and transportation in different climates today we can deduce the climate under which rocks were formed in the past. For example, both the shape of individual sand-grains and the structure of sandstone from Permian rocks which are common in northern England, are similar to those found in the Sahara today. This indicates that 280 Ma ago sands in Britain were being deposited in hot desert conditions. Present-day glaciers elsewhere can be seen to be eroding the landscape to leave characteristic land forms. Similar land forms found in Britain are interpreted as evidence that 20 000 years ago much of Britain was covèred by an ice-sheet.

This approach has already been referred to as the present being the key to the past. It was Hutton's work which first led to this **principle of uniformitarianism**, as it is called. Unlike many of his predecessors, Hutton always carefully reported actual observations and, in fact, was among the first to look at events in terms of what we would now call the geological cycle. He argues that mountains are shaped and ultimately destroyed by weathering and stream erosion, and that fragments of the rocks forming the mountains are carried to the sea. Hutton stated: 'There is not one step in all this . . . that is not to be actually perceived' and then he tested the model by asking 'What more do we require?', to which he supplied the answer: 'Nothing but time'. Exactly how much time was involved in the Earth's history was a problem to be tackled later by other scientists.

3.5 THE STRATIGRAPHIC COLUMN

In examining both the generalized Stratigraphic Column (back cover) and the more detailed ones for southern Britain (Figures 14 and 15), you may have wondered how the names of the various Periods were derived. The Palaeozoic Era is composed of six Periods: the three lower ones were first recognized in Wales but not without some controversy between Adam Sedgwick (1785–1873) and Robert Murchison (1792–1871). Both began mapping the undifferentiated 'Killas, or Slate' at the base of Smith's column (Figure 14). Murchison started with the distinctive Old Red Sandstone

(Devonian) in South Wales and established a sequence of strata, each group characterized by particular fossils, working down the Stratigraphic Column. For this sequence he introduced the name Silurian, from the name of a tribe, the Silures, who inhabited a part of South Wales at the time of the Roman occupation of Britain. Sedgwick concentrated his studies in North Wales. He was at a disadvantage compared with Murchison because he did not have a reference level to work from in the Stratigraphic Column, like the Old Red Sandstone. But after several years he was able to work out a succession of the strata that he was mapping for which he proposed the name Cambrian, after Cambria, the Roman name for Wales.

At the time these two Periods were proposed, neither Murchison nor Sedgwick had any clear idea how they related to each other. It was discovered some years later that the lower part of Murchison's Silurian contained the same fossils as those in the upper part of Sedgwick's Cambrian. This discovery led Murchison to conclude that all of Sedgwick's Upper Cambrian was merely a part of the Silurian—a conclusion strongly opposed by Sedgwick. The argument turned a warm friendship into enmity that lasted the lifetime of the two men. Finally in 1879, after both were dead, another geologist, Charles Lapworth, proposed the name Ordovician, after the tribe which had occupied North Wales, to include the Upper Cambrian of Sedgwick and Lower Silurian of Murchison. The proposal was accepted and so the Ordovician now separates the rocks of the two rivals in the Stratigraphic Column.

If you are interested in the origins of the other Period names, have a look at Table 4. The Periods, once they had become established, together with other stratigraphic names, became part of an international geological terminology which could be applied all over the world.

TABLE 4 Origin of the names of the Periods in the Stratigraphic Column

Eras		Periods	Age of base/ Ma	Country where defined	Author	Year defined	Derivation of name
CAINOZOIC (recent life)		QUATERNARY					
		Holocene					Holos: whole*
		Pleistocene	2	England	Lyell	1829	Pleiston: most
		TERTIARY					
		Pliocene		England	Lyell	1833	Pleios: more
		Miocene		England	Lyell	1833	Meion: less
		Oligocene		Germany	Beyrich	1854	Oligos: few
		Eocene		England	Lyell	1833	Eos: dawn
		Palaeocene	65	Germany	Wilhelm Schimper	1874	Palaios: old
MESOZOIC (middle life)		CRETACEOUS	145	France	d'Halloy	1822	Creta: chalk
		JURASSIC	215	Switzerland	Humboldt	1795	Jura Mountains
		TRIASSIC	250	Germany	Alberti	1834	Threefold division recognized in Germany
PALAEOZOIC (ancient life)	UPPER	PERMIAN	285	Russia	Murchison	1841	Perm: Russia
		CARBONIFEROUS	360	England	Conybeare and Phillips	1822	Coal: Carbon
		DEVONIAN	410	England	Murchison and Sedgwick	1840	Devon
	LOWER	SILURIAN	440	Wales	Murchison	1835	Silures: Welsh border Celts
		ORDOVICIAN	505	Wales	Lapworth	1879	Ordovices: Celts of N. Wales
		CAMBRIAN	590	Wales	Sedgwick	1835	Cambria: Latin for Wales

* Sir Charles Lyell recognized that in the Cainozoic Era modern species appear as fossils, becoming progressively more abundant in younger sediments. (For example, 3% of Eocene species are alive today, and as many as 30–50% of Pliocene species exist today. He therefore used Greek prefixes to subdivide the Cainozoic.

ROCK-STRATIGRAPHIC COLUMN

BED

BEDDING PLANE

ZONE

BIOSTRATIGRAPHIC COLUMN

ABSOLUTE DATING METHOD

As you may have begun to realize, the Stratigraphic Column can be considered in several different ways, according to how the units of geological history are defined and measured. There are three main methods of doing this.

First to be recognized were distinctive sedimentary rock units, such as the Chalk and the Coal Measures, and a column can be built up by arranging these units in their correct order to form a **rock-stratigraphic column**. (Smith's column, Figure 14, is an example of this.) The smallest unit in this column is an individual **bed** of a particular rock type, which is separated from the beds above and below by **bedding planes**, as shown in Figure 18. In different parts of the world, rock units of the same age may be quite different, reflecting the different conditions of deposition, so a locally distinctive rock unit cannot always be found elsewhere. A way of defining the Stratigraphic Column that can be applied more widely is therefore needed.

FIGURE 18 Photograph of horizontal strata, to show bedding planes, separating individual beds of sedimentary rock. Beds of harder (lighter) limestone alternate with softer (darker) shales, Lower Lias (Jurassic), Dorset.

By using the time span of fossils, the Stratigraphic Column can be divided into **zones**. These define the **biostratigraphic column**. A zone may be defined for a short time-range such as that of an individual species which may have lived for less than a million years, up to that of a succession of related species which may have lived for several tens of Ma. Each Period is made up of a whole series of zones and zone fossils. In a crude sort of way the 'age of the dinosaurs' is such a biostratigraphic unit, albeit a large one, spanning more than one Period in the Stratigraphic Column (see Figure 6).

Finally, it has been possible to get radiometric dates for some rocks in the Stratigraphic Column, and to express their ages in millions of years. Thus the time interval of each Period is now known quantitatively (Figure 15) and so it is possible to say, for example, that the Cambrian Period lasted 85 Ma. This puts *actual dates* to the already established sequence of Periods of geological time, and is an example of an **absolute dating method**, although, like all physical measurements, these dates are subject to a degree of uncertainty.

SUMMARY OF SECTION 3

In this Section we have taken the simple concept of stratigraphic sequence from Section 2 and have shown how this has been built up by 18th- and 19th-century geologists into a detailed and sophisticated Stratigraphic Column. Implicit in this approach are three fundamental principles:

1 the principle of superposition; younger rocks are deposited on top of older rocks;

2 the principle of faunal succession: there is a definite sequence of fossils for each part of geological history and this sequence is the same wherever it occurs;

3 the principle of uniformitarianism: geological processes operating at present also operated in the past.

A simplified Stratigraphic Column is shown in Figure 15, in which geological time is divided into four Eras. The earliest, the Precambrian, cannot easily be further subdivided due to much poorer fossil evidence, but the remaining three Eras have been divided into eleven Periods, which in turn can be further subdivided. The sedimentary rocks that occur in any part of Britain can be assigned to a position on the Stratigraphic Column, thus giving them an age relative to other sedimentary rocks.

SAQ 6 Did William Smith's application of the principle of faunal succession imply that he was interpreting Earth history in terms of either uniformitarianism or catastrophism, or in terms of neither idea?

SAQ 7 Suppose you are asked to make a stratigraphic column of an area which consists largely of one rock type, a mudrock with some fossils. How would you define different units in your column: in terms of (a) rock units, (b) fossil zones, or (c) time periods?

4 ABSOLUTE MEASUREMENT OF GEOLOGICAL TIME

After a brief description of two early attempts to estimate geological time, this Section describes how the exponential decay of radioactive isotopes of certain elements which occur in some minerals can be used to calculate ages for the formation of rocks. Since radiometric dating is a quantitative method, you will be asked to calculate actual ages yourself with your calculator or by log–linear graphs. This is the most tricky Section of the double Unit; you should make sure you work through it carefully.

4.1 EARLY ESTIMATES OF GEOLOGICAL TIME

By the 1840s the major divisions of the Stratigraphic Column had been worked out and geologists could begin to tackle the problem of how much time was represented by each unit in the Column. The principles of uniformitarianism, propounded by Hutton, and of faunal succession, produced by Smith, were put together by Sir Charles Lyell (1797–1875).

Lyell had little patience with geologists whose theories were not based on observation of present-day processes; he believed strongly in 'existing changes' (now called the principle of uniformitarianism). Lyell expressed his views on this very forcefully:

> It appeared that the earlier geologists had not only a scanty acquaintance with existing changes, but were singularly unconscious of the amount of their own ignorance.

PARENT ISOTOPE

DAUGHTER ISOTOPE

And of catastrophism he wrote:

> Never was there a dogma more calculated to foster indolence, and to blunt the keen edge of curiosity than this assumption of the discordance between the ancient and existing causes of change.

To try to begin to work out the scope of geological time, Lyell looked for present-day rock-forming processes whose rates he could measure. From these direct observations, the time taken for the accumulation of comparable sedimentary rocks could then be estimated. For example, Lyell calculated the age of sediments deposited in present-day deltas and concluded that although by historic standards these deltas were old, geologically they were very young. The Earth, he concluded, must be many millions of years old.

Towards the end of the 19th century, the physicist Lord Kelvin made another quantitative estimate of the age of the Earth. Kelvin clearly preferred quantitative methods:

> I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind. (Lecture by Lord Kelvin to the Institute of Civil Engineers, 3 May 1883)

Kelvin assumed that the Earth had been cooling ever since its formation from a molten mass, by conducting heat to the surface and then by radiating it into space, and that it had no continuing internal source of heat. On this assumption, a maximum age could be calculated from the Earth's inferred rate of cooling, by using measurements of heat flow. His result for the age of the Earth was between 20 and 40 Ma.

At that time no one was aware of the main fallacy in his argument: contrary to his assumptions, heat *is* being produced inside the Earth.

□ What is the nature of the source of this internal heat?

■ Radioactive decay of the naturally occurring isotopes of elements such as uranium, potassium and thorium.

In fact, although based on quantitative data, the calculations of Lyell and Kelvin both gave gross underestimates of the Earth's age.

4.2 RADIOMETRIC 'CLOCKS'

Rocks that have minerals containing a radioactive isotope have a built-in 'clock' for measuring their age. The principle is very simple. The rates of decay of all the common radioactive isotopes are constant and are known from accurate laboratory measurements on pure samples. If the amount of a radioactive isotope present in a material when it was formed is known, then the age of that material can be calculated from its present radioactivity, using the known decay rate for that isotope. You have already met this method of radioactive dating in Units 11–12, Section 4.2, where the decay of $^{14}_{6}C$ in wood was described. In the case of wood, the proportion of $^{14}_{6}C$ originally present is known because $^{14}_{6}C$ is generally constant in the atmosphere and in living tissues which are in equilibrium with the atmosphere. After death, the decay of $^{14}_{6}C$ to $^{14}_{7}N$ in the tissues results in a progressive loss of $^{14}_{6}C$ with time, and the age of a sample can be calculated from the proportion of $^{14}_{6}C$ left in it compared with the proportion in present living tissue. The half-life for this decay scheme is 5 700 years. Remember that the half-life is the time taken for half of the number of atoms of an isotope to decay.

ITQ 7 Why is the $^{14}_{6}C$ method not suitable for dating most geological events?

TABLE 5 Naturally occurring radioactive isotopes

Isotope	Approx half-life/years
$^{22}_{11}Na$	2.6
$^{137}_{55}Cs$	30
$^{235}_{92}U$	7×10^8
$^{40}_{19}K$	1×10^9

□ Consider the naturally occurring radioactive isotopes listed in Table 5. Which ones might be most useful for geological dating?

■ The last two, since they have half-lives of hundreds or thousands of millions of years, which is of the same order of magnitude as geological events.

Most geological ages are calculated from radioactive decay in which the original **'parent' isotope** decays to give a stable **'daughter' isotope**. To calculate the age of a mineral grain, it is necessary to find out how much of the parent isotope has decayed since the mineral was formed. This is normally done by measuring the amount of daughter isotope present, as well as the amount of parent isotope left, to obtain the parent : daughter ratio.

The nature of the rate of radioactive decay is shown in Figure 19. You have met radioactive decay equations before in Units 11–12, Section 4.2, and you should remember that the rate of radioactive decay is exponential, not linear.

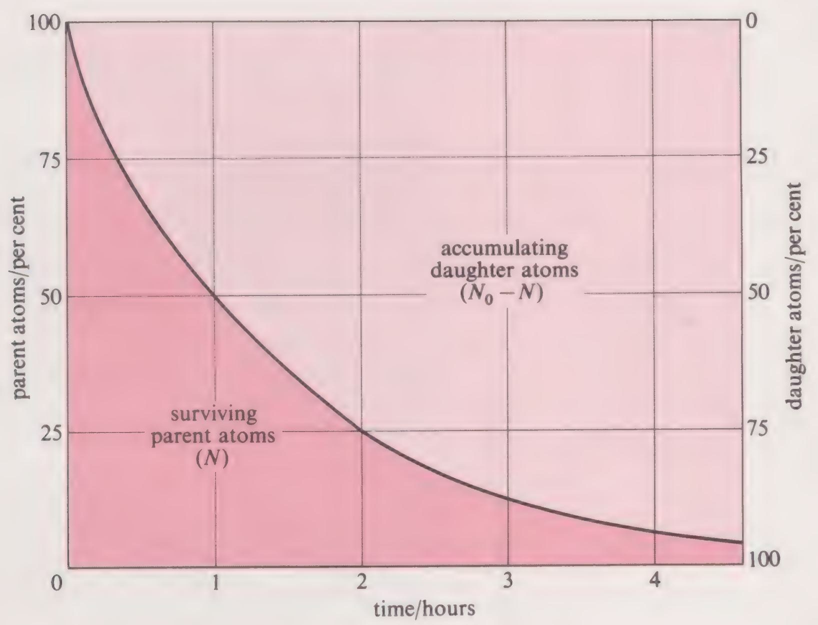


FIGURE 19 Example of exponential decay: N_0 = original number of parent atoms; N = number of parent atoms at any subsequent time.

If N_0 is the number of original parent atoms, and the number of those surviving after n half-lives is called N, the decay process can be expressed by:

$$N = N_0 \times (\tfrac{1}{2})^n \quad (1)$$

(You have met Equation 1 before as Equation 6 in Units 11–12.) From Figure 19 you can see that in the first hour half the radioactive parent decays. But during the second hour only a further quarter of the original radioactive parent decays (half of the total left after the first hour). After 4 hours $(\frac{1}{2})^4$ or $\frac{1}{16}$ of the original parent atoms are left and $\frac{15}{16}$ of the total possible daughter atoms have been formed. You have already met a graph of this shape when considering $^{14}_{6}C$ dating (Units 11–12, Figure 14).

□ Look at Figure 19. What is the half-life of this radioactive isotope?

■ One hour. In each hour the amount of parent isotope falls to half of its former value.

It is possible to work out the ages of minerals by plotting the information on parent and daughter isotopes on a graph. When one quantity that changes by several orders of magnitude is to be plotted against another that changes more slowly, it is convenient to plot the rapidly changing quantity on a logarithmic scale. (This is equivalent to plotting the log of the quantity on a linear scale.)

ITQ 8 (a) Use Figure 20 to replot the data from Figure 19 on a logarithmic scale. In order to plot the amount of parent isotope remaining against time on Figure 20, look again at Figure 19. Clearly you should start at time 0 with 100% of the parent isotope, that is, at the top left-hand corner, and then plot the percentage of remaining parent isotope after each hour. Since the half-life here is one hour, the horizontal scale can be read in either half-lives or hours. If you join up the points you should find the data lie on a straight line. Such an array is obviously useful for extrapolating beyond the data or obtaining intercepts, and this is one reason why logarithmic scales are used to plot exponential decay.

(b) How long does it take for the parent : daughter ratio to be 1 : 500?

(c) How long does it take for the parent : daughter ratio to be 1 : 5 000?

Obviously, to be useful, a radiometric clock must operate on a time-scale of the same order of magnitude as the process being timed. The amounts of radioactive isotopes in most rocks are very small, usually measured in parts per million. Furthermore, as you have seen in ITQ 8(c), after about 12

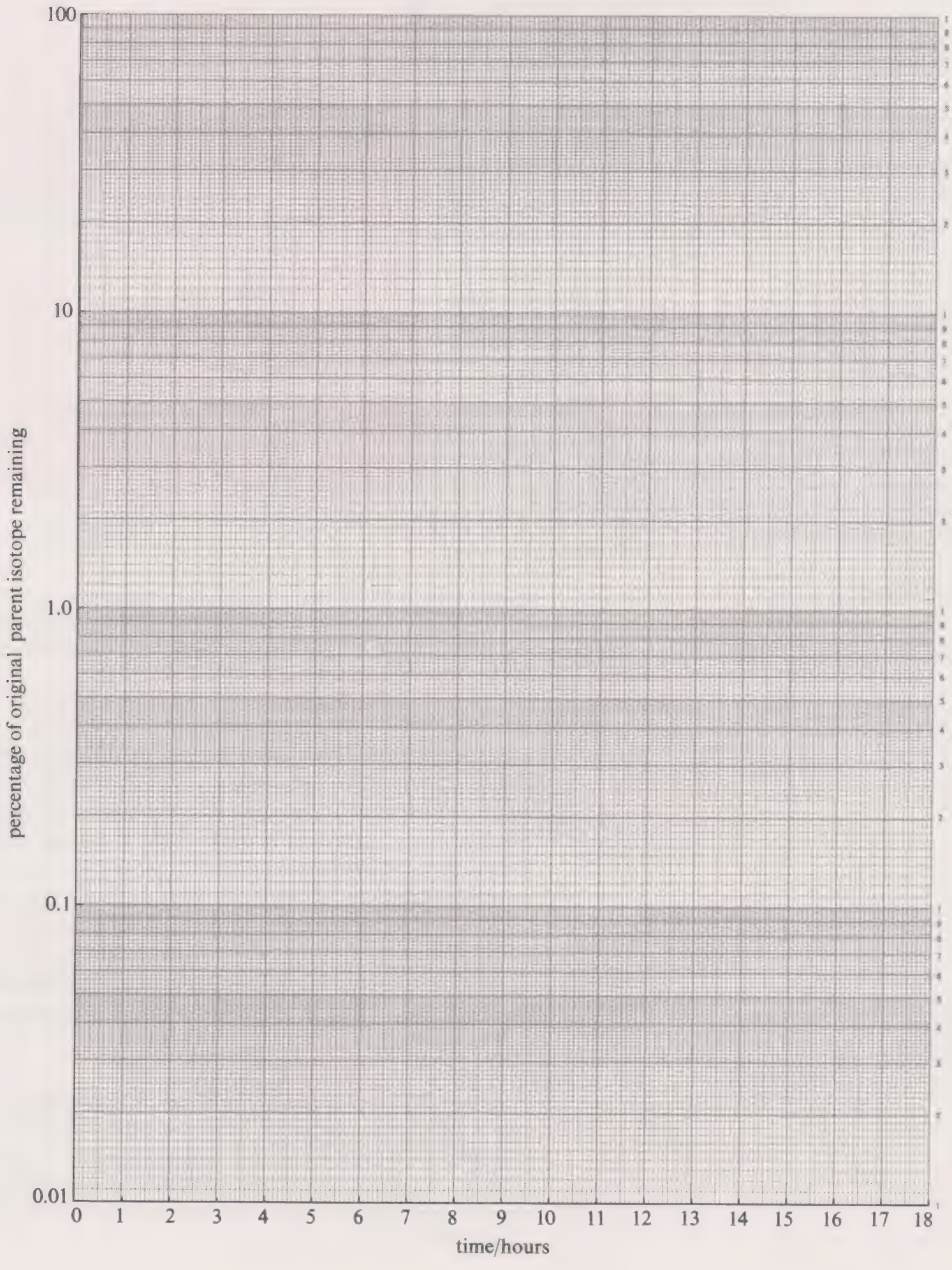


FIGURE 20 Log–linear graph for use with ITQ 8.

half-lives the parent : daughter ratio falls to 1 : 5 000; that is, the parent isotope practically disappears. To use the parent : daughter ratio for dating rocks we need to know the amounts of both isotopes very accurately. If they were in the ratio 1 : 5 000 this would clearly present severe measuring problems! For this reason, all radiometric ages have an uncertainty, usually $\pm 1\%$ to 2%, due largely to the difficulties in measuring the very small quantities of isotopes present in the samples.

ITQ 9 If the original sample in Figure 19 contained 10^{10} atoms of parent isotope at time 0 how many would remain after 6 hours, that is, after six half-lives?

There is another way to use Equation 1. Look again at Figure 19. This time, suppose you did not know how long the radioactive decay had been going on, but had been told that the half-life was 1 hour, and that the present parent : daughter ratio is 1 : 500.

□ Can you calculate when the decay started (that is, the age of the sample)?

■ You need to find n, the number of half-lives that have elapsed. Starting with Equation 1:

$$N = N_0 \times (\tfrac{1}{2})^n \qquad (1)^*$$

Rearranging, $N/N_0 = (\frac{1}{2})^n$

In order to obtain n from this equation, we must take logs,

$$\log (N/N_0) = n \log (\tfrac{1}{2})$$

Therefore, $n = \log (N/N_0)/\log (\frac{1}{2})$ (2)

We know that the present parent : daughter ratio is 1 : 500. In other words, for 500 daughter atoms there is 1 remaining parent atom.

In algebraic terms,

$$(N_0 - N) = 500 \qquad \text{and } N = 1.$$

Therefore, original number of parent atoms $(N_0) = 501$.

Using Equation 2,

$$n = \log (1/501)/\log (\tfrac{1}{2})$$

So the number of half-lives, $n = 8.97$.

The half-life is known to be one hour, so the age of the sample is 8.97 hours.

This is an example of a radiometric age calculation: the age is calculated in terms of the number of half-lives (n), from the present parent : daughter ratio $N/(N_0 - N)$ by using Equation 2. Note that n is the number of half-lives and, to obtain the age of the sample (t), it has to be multiplied by the half-life of the radioactive decay process, represented by τ (the Greek letter tau):

$$t = n \times \tau$$

The units of the age calculated will be the same as the units of the half-life, normally millions of years, so to get the age in millions of years we replace n by t/τ in Equation 2 to give:

$$t/\tau = \log (N/N_0)/\log (\tfrac{1}{2})$$

or $\boxed{t = \tau \log (N/N_0)/\log (\tfrac{1}{2}) \qquad (3)}$

Hence, given the parent : daughter isotope ratio and the half-life of the decay process, we can determine an age either by calculation (Equation 3) or graphically (ITQ 8).

4.3 MINERALS AS RADIOMETRIC CLOCKS

There are several radioactive decay processes that have been used for geological dating, and a selection is shown in Table 6.

□ So how is a rock sample dated? What kind of mineral can be used for dating?

■ The mineral must have contained atoms of a radioactive isotope when it originally crystallized without any of the daughter isotopes at the time of crystallization. Each parent atom eventually decays to a daughter isotope which is retained in the same crystal.

TABLE 6 Radioactive decay processes commonly used for dating rocks

Parent isotope		Daughter isotope	Half-life
$^{238}_{92}U$	$\longrightarrow$	$^{206}_{82}Pb$	4 467 Ma
$^{235}_{92}U$	$\longrightarrow$	$^{207}_{82}Pb$	704 Ma
$^{40}_{19}K$	$\longrightarrow$	$^{40}_{18}Ar$	1 193 Ma
$^{87}_{37}Rb$	$\longrightarrow$	$^{87}_{38}Sr$	48 800 Ma

Suppose we find an igneous rock containing a uranium-rich mineral and that when it initially crystallized, it did not incorporate any lead in the crystals. As time passed, some of the uranium would have been converted to lead by radioactive decay. To find out how old the rock is, samples of the mineral can be dissolved to get the uranium and lead into solution. The parent : daughter ratios of the isotopes $^{235}_{92}U : ^{207}_{82}Pb$ and $^{238}_{92}U : ^{206}_{82}Pb$ can then be measured with a mass spectrometer.

Consider the decay of $^{235}_{92}U$ to $^{207}_{82}Pb$. Since one atom of uranium decays to yield one atom of lead, and both the amounts of parent (N) and daughter ($N_0 - N$) isotopes present now can be measured, the age of the sample can be calculated from the known half-life of the parent isotope (τ), 704 Ma, by using Equation 3. Figure 21 shows diagrammatically how the proportions of these two isotopes have changed with time.

This simple dating procedure will work only if the following assumptions are true:

(a) there is no production of $^{235}_{92}U$ or $^{207}_{82}Pb$ by any other radioactive decay process;

(b) all the $^{235}_{92}U$ and $^{207}_{82}Pb$ have been retained within the mineral since its time of formation;

(c) no $^{207}_{82}Pb$ was originally present.

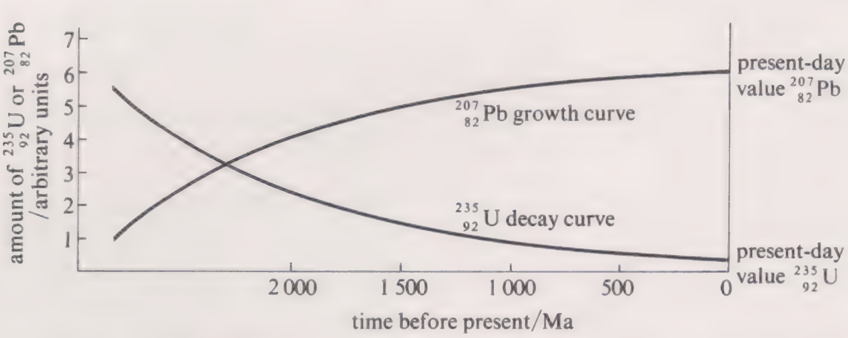


FIGURE 21 The changing proportions of $^{235}_{92}U$ and $^{207}_{82}Pb$ with time. The decay curve for the parent isotope, $^{235}_{92}U$, is a mirror image of the growth curve of the daughter isotope, $^{207}_{82}Pb$.

ITQ 10 (a) A grain of an originally lead-free mineral that contained uranium was found to have equal isotopic proportions of $^{235}_{92}U$ and $^{207}_{82}Pb$. How old is the mineral grain? (Refer to Table 6).

(b) If a similar mineral from another rock contained fifteen times as much $^{207}_{82}Pb$ as $^{235}_{92}U$, how old is it?

The simplest rocks to use for radiometric dating are igneous ones, in which all the mineral grains are formed by crystallization from the magma at about the same time. If a mineral that contained no daughter isotope when it crystallized is isolated today, the radiometric date that is determined is the date of crystallization, when the parent isotope was 'locked up' in a crystal and the radiometric clock 'started to tick' inside the mineral. A good example of a mineral often used for dating igneous rocks is zircon, since this contains some uranium but virtually no lead at the time of crystallization.

In metamorphic rocks, in which some recrystallization of the minerals may have occurred as a result of the rocks being heated, radiometric ages may reflect the date at which a metamorphic event took place. If the whole rock recrystallizes during metamorphism, then any daughter atoms produced before that time may escape from the mineral grain in which they were formed to move away from the remaining parent isotope. Thus, the radiometric clock has been restarted, and so age determinations for that mineral will give the date of the metamorphism. An example of a decay system that is easily 'reset' is ${}^{40}_{19}K$ to ${}^{40}_{18}Ar$. Argon, the daughter isotope, is a gas and can escape from the mineral at temperatures much lower than the temperature at which the mineral originally crystallized. Hence the dating of micas (which at the time of their formation contained potassium but no argon) will only give the age of original crystallization if the rock has not been reheated during its geological history. For metamorphic rocks, therefore, the K–Ar decay will date the metamorphic age rather than the age of original crystallization.

□ Can you see why it is normally difficult to date sedimentary rocks by radiometric methods?

■ Because sediments are normally formed by the accumulation of pre-existing mineral grains, the radiometric age determined from a sedimentary mineral would normally be that of the rock from which the grain came. Thus a particular grain in a sandstone may yield a radiometric age of the igneous rock from which the original mineral grain came, and could be thousands of Ma older than the deposition of the sediment.

SUMMARY OF SECTION 4

Geological time is measured using the decay processes of naturally occurring isotopes. Measurement of the parent and daughter isotopes in a rock or mineral where the half-life of that decay system is known means that an age can either be calculated (Equation 3) or estimated graphically (ITQ 8). This age will be the age at which the rock or mineral was formed provided that:

1 the daughter isotope has not been lost since formation;

2 no daughter isotope was present at the time of formation.

Absolute dating allows the age of igneous rocks to be measured but it cannot measure directly the time of deposition of a sedimentary rock.

SAQ 8 If you had a series of samples of uranium-containing minerals which you thought were about 500 Ma old, would

$${}^{235}_{92}U \longrightarrow {}^{207}_{82}Pb \quad \text{or} \quad {}^{238}_{92}U \longrightarrow {}^{206}_{82}Pb$$

be the better radiometric clock to use for measuring the most accurate dates? (See Table 6.)

SAQ 9 If a mineral sample from an igneous rock gave an isotopic ratio of ${}^{235}_{92}U : {}^{207}_{82}Pb$ of 1 : 20, how old was the rock from which it came?

SAQ 10 If half of the lead in the mineral from SAQ 9 was present when the mineral crystallized, how does this affect its calculated age?

CONTACT METAMORPHISM

SILL

5 CALIBRATING THE STRATIGRAPHIC COLUMN

So far this double Unit has demonstrated how sedimentary rocks can be dated relatively, and igneous rocks dated absolutely. How can the two time-scales be combined?

5.1 IGNEOUS ROCKS AS CALIBRATION POINTS

As an igneous magma cools and minerals containing a radioactive isotope crystallize, the radiogenic 'clock' is started in the rock, so that at any subsequent time the age of cooling can be determined by the methods described in Section 4. Although igneous rocks are found relatively rarely interstratified with sedimentary rock that can be dated by fossils in the Stratigraphic Column, when this happens the igneous ages provide crucial calibration points, since they can give an exact age in millions of years to that part of the Stratigraphic Column. The best examples are lavas, which *postdate* the rocks beneath and *predate* overlying strata: in other words, the adjacent sediments bracket the position of the lava on the Stratigraphic Column, which can then be dated isotopically to provide an 'absolute' age.

But not all magma reaches the Earth's surface, and, if magma solidifies by infilling fissures or larger spaces in the crust, the igneous rocks that result can be shown to be later than the surrounding rocks because the igneous rocks may *cut across pre-existing structures such as bedding planes.* The heat and fluids from cooling magma may also cause physical changes in the surrounding rocks by recrystallization and growth of minerals only stable at high temperatures. This process you know from Unit 27 as **contact metamorphism**. Often an intrusive rock itself may show the effects of rapid cooling where it has come in contact with the surrounding strata.

An igneous rock that is intruded as a sheet along a bedding plane is called a **sill**. Sills are often from a few metres to several tens of metres in thickness and spread over an area of many tens or hundreds of square kilometres at roughly the same horizon in a sedimentary sequence (Figure 22a). A crack which cuts across the strata and is filled with magma is known as a dyke (Figure 22b). Sills, dykes and lava flows, which can be radiometrically dated, are all used for bracketing the ages of sedimentary rocks in which they are found.

In a similar way, large intrusions, which often represent many cubic kilometres of magma, and which have crystallized at a depth of several kilometres, can also be used to determine a minimum age for the surrounding rocks.

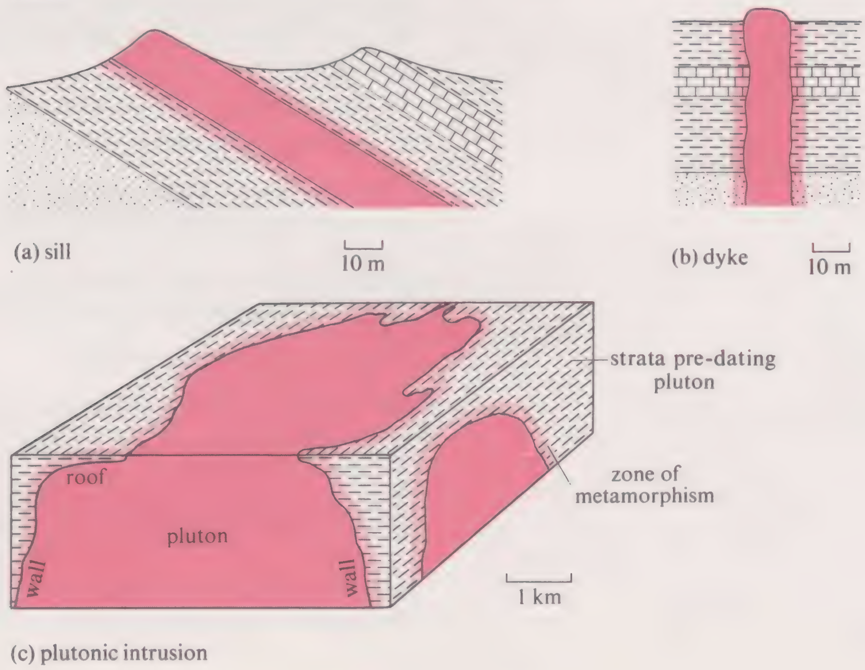


FIGURE 22 Various types of igneous intrusions. (a) Cross-section of sill. The beds above and below are likely to have been baked (pale pink) by the intrusion (dark pink). (b) Cross-section of dyke. The rocks on both sides of the dyke may show the effects of baking by the intrusion. (c) Block diagram of a pluton. The zone of contact metamorphism around the igneous rock may be quite extensive.

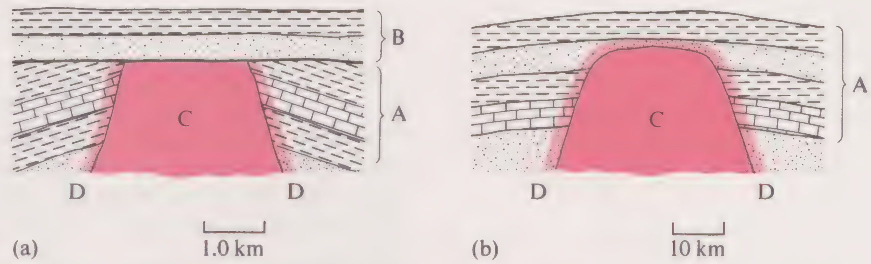


FIGURE 23 Diagrammatic sections through plutonic intrusions. (a) Plutonic rock, C, has intruded strata A, forming a zone of contact metamorphism, D. After a period of uplift and erosion to expose the plutonic rock, a second series of sediments, B, were laid down above the unconformity. Pebbles of rocks A, C and D may occur in beds B. Beds A are older than the igneous rock, C; beds B are younger than C. (b) Plutonic rock, C, has intruded beds A, and formed a zone of contact metamorphism, D. Here all the strata around the intrusion are older than C and therefore there is a zone of contact metamorphism all around the intrusion.

☐ Can you recall (from Units 7–8) what kind of rock usually occurs in these large plutonic intrusions (Figure 22c), and where, in plate-tectonic terms, they are often found?

■ They are composed of granite, and commonly occur above *destructive* plate margins.

The relationships seen in the field between an igneous intrusion and the surrounding sedimentary rocks are very important if the igneous rocks are to be used for dating purposes. For example, a granite may cut across the bedding of the adjacent strata and therefore must be later than those strata (Figure 23b), or the contact between granite and sediments may be an unconformity, in which case the granite is older than the overlying sediments and does not metamorphose them at all (Figure 23a).

ITQ 11 Look at Figure 24, which shows in each case two sedimentary beds A and B and an igneous rock (shaded).

(i) Which diagram shows a lava?

(ii) Which diagram shows a sill?

(iii) Which diagrams show a dyke?

(iv) In which three diagrams will a radiometric age for the igneous rock give a *minimum* age for both A and B?

(v) In which two diagrams will a radiometric age for the igneous rock give a *minimum* age for A and a *maximum* age for B?

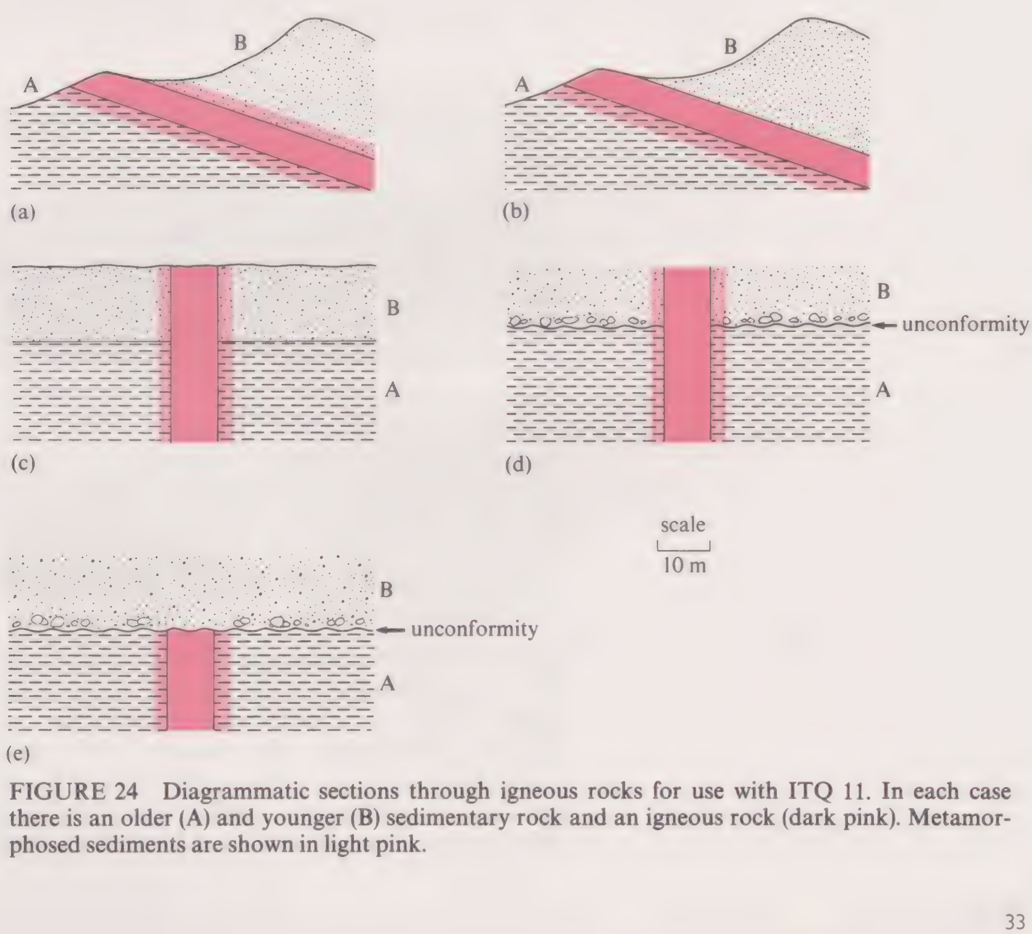


FIGURE 24 Diagrammatic sections through igneous rocks for use with ITQ 11. In each case there is an older (A) and younger (B) sedimentary rock and an igneous rock (dark pink). Metamorphosed sediments are shown in light pink.

5.2 DATING A GRANITE (TV PROGRAMME)

In this TV programme you will see how it is possible to 'bracket' the age of an igneous intrusion by looking for fossils that pre-date and post-date its intrusion, and that the uncertainty in the age is often quite large. When samples are taken from a particular granite and radiometric dates calculated from individual minerals separated from it, much more precise dates are obtained, leaving little room for debate.

For the first part of the programme, you might find it helpful to look at Plates 27–29, showing models used in the programme.

As you watch the programme, try to note down what seem to be the crucial steps in the argument, and afterwards try to fill in the dates of the various events that are discussed in the programme by attempting ITQ 12.

ITQ 12 What is the age of Shap granite? Complete the following:

(a) Relative age of Shap granite from fossil evidence: Maximum age, from fossils in beds cut by Shap granite, dating from the .... Period .... Ma. Minimum age, from fossils in beds overlying Shap granite, dating from the .... Period .... Ma).

(b) Absolute age of zircon crystals in Shap granite: ...... Ma ± .....Ma. Absolute age of mica crystals in Shap granite: ...... Ma ± .....Ma.

At the end of the programme, the granite below Alston is shown by the Rookhope borehole (Plate 29) to be *earlier* than Lower Carboniferous (cf. Figure 23a), and so the mineralization cannot have come from the cooling granite. It is now believed that the lead mineralization resulted from the redistribution by water of minerals already present in the Carboniferous strata in post-Carboniferous times.

5.3 SUB-DIVIDING THE STRATIGRAPHIC COLUMN

Each time a particular radiometric date is used to calibrate some part of the Stratigraphic Column, a similar age can then be applied to rocks known to be of the same age because they contain similar fossils. Moreover, in a uniform series of sediments, if radiometric ages can be found for several strata in a sequence, the age range of rocks between can be estimated. Each new radiometric date can then be used to refine the dating of the Column.

Some unconformities, representing geological events that can be recognized over wide areas, can be dated quite precisely, and many of the geological Periods in the Stratigraphic Column are separated from the rocks above and below by such unconformities. The use of the palaeomagnetic reversal time-scale to establish the details of events of the past 4.5 Ma has already been discussed (Units 5–6, Section 5). The dates for this time-scale again depend on the determination of real radiometric ages of some of the igneous rocks involved.

By the detailed correlation of these dates for igneous rocks from all parts of the world, virtually any strata later than the Precambrian in the Stratigraphic Column can now be dated. However, the individual zone, defined by fossils, remains the unit of calibration for the practising geologist in the field. Marker horizons, often characterized by one or more specific fossils, are used to establish the relative ages of individual outcrops. This is basically the same method used by William Smith nearly 200 years ago.

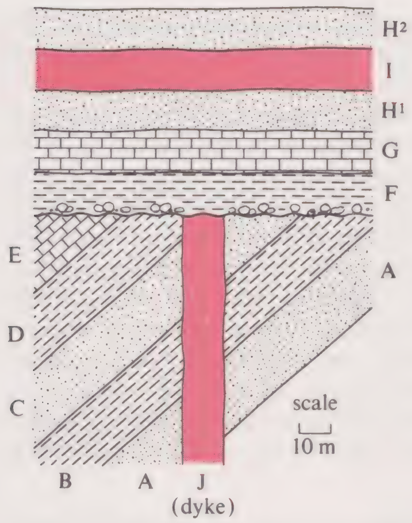


FIGURE 25 Cross-section of a quarry face (for use with SAQ 11).

It is in the unravelling of Precambrian events, however, that radiometric dating has been most useful. In the Precambrian there are abundant igneous and metamorphic rocks that yield radiometric dates, but there is a far from complete sedimentary record. We now know that the Palaeozoic and more recent sediments, with their abundant fossils, represent little more than 10% of the Earth's history, which stretches back to 4 600 Ma. We believe that processes similar to those we can now observe at the Earth's surface have been going on for more than two thousand million years, and we believe that the most recent episode of continental fragmentation and sea-floor spreading, which you studied in Units 7–8, Section 4, is just the latest of many such episodes.

SUMMARY OF SECTION 5

The relative dating of strata and the absolute dating of igneous rocks can be combined by careful field observations of lava flows, dykes and sills and the strata with which they are associated. The Shap granite presents a specific example where the relative age of the strata it intrudes is known from fossil evidence, and the absolute age is known from isotopic analysis of minerals from the granite. In this way the Stratigraphic Column can be 'calibrated' with absolute ages, as shown on the back cover of this binding.

SAQ 11 Look at Figure 25. There are two series of sedimentary rocks (A–E and F–H^2) and two igneous intrusions, a dyke (J), and a sill (I).

(a) Which are the rocks of the older sedimentary series, and which the younger?

(b) Is igneous rock I or J the older, and why?

(c) Arrange the rocks in four age groups, starting with the oldest.

(d) What is the surface at the base of rock F?

(e) If rock I were a lava flow, would that affect your answer to (c)?

SAQ 12 (a) Is the granite in Figure 26a older or younger than the strata A–D? Give reasons for your answer.

(b) Is the granite in Figure 26b older or younger than the strata X–Z? Give reasons for your answer.

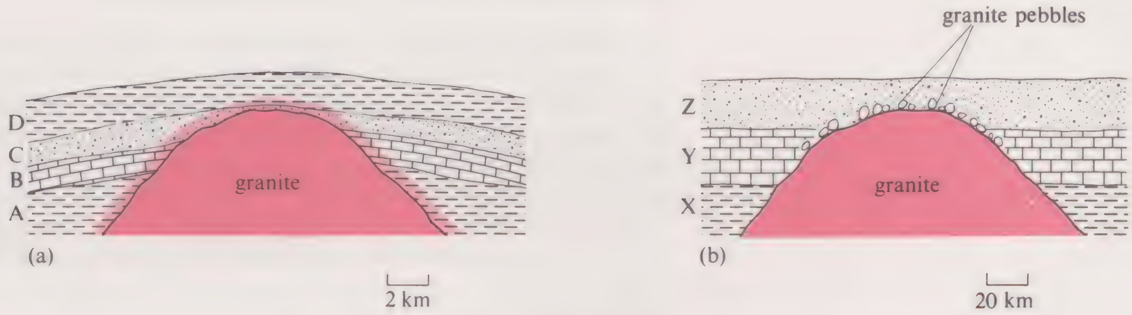


FIGURE 26 Cross-section of granite intrusions (for use with SAQ 12).

6 HOW OLD IS THE EARTH?

So far, we have considered the use of minerals and rocks from igneous bodies as geological clocks which measure the time that has elapsed since the rock was molten. Individual minerals can be recrystallized by heating, and, if this happens, the clock is reset. Consequently geologists often measure the ages of whole igneous rock samples (not just minerals separated from the rock) which will provide the age at which the complete rock

NEBULA

was formed, rather than the time of reheating of a particular mineral. The most commonly used decay system for this approach is $^{87}_{37}Rb$ to $^{87}_{38}Sr$ (see Table 6) although the presence of strontium in virtually all rocks at the time of their formation means that this must be allowed for in calculating the age. The oldest rock age given by this method is about 3.8×10^3 Ma for granites from Greenland. For the oldest ages recorded in any igneous rocks on Earth we must return to minerals. A technique developed in the 1970s uses an ion microprobe to analyse the isotopes present in a solid target only a few micrometres across, thus dispensing with the laborious process of crushing rocks, separating minerals and dissolving the samples in strong acids. In this way, not only individual minerals, but minute areas within a mineral crystal can be dated. Individual zircon crystals from Australia studied by this technique have yielded ages of 4.2×10^3 Ma. Thus, with refinement of dating techniques, minerals and rocks are yielding records of older events in the Earth's history. How can the age of the Earth itself be measured?

The answer lies in combining two very different kinds of analysis. Uranium and lead isotopes are measured from sediments that have been deposited in the deep-ocean basins. The sediments are composed of particles that have been eroded from all kinds of rock exposed at the Earth's surface and therefore represent a reasonable estimate of an average crust composition. Measuring the uranium and lead isotopes in a particular mineral in the sediment dates the crystallization of that mineral, so the date records the age of crystallization of the igneous rock from which the sediment was derived. However, the isotopes from *all* the minerals in the sediment are derived from many different igneous bodies. Although the details of this approach are beyond the scope of this Course, the dates obtained by analysing U and Pb isotopes from whole-rock samples of the deep-sea sediments give the age at which all the sedimentary sources were part of the same magmatic system or reservoir—in other words, the time at which all the contributing igneous bodies were part of a homogenous magma in the early history of the Earth. In the case of deep-sea sediments these give us approximate ages of between 6.7×10^3 and 5.5×10^3 Ma. This is only half the story, however, because we do not know how much daughter isotope (either one of the two lead isotopes in Table 6) was present at the formation of the Earth. Since lead is a common terrestrial element and is found even in meteorites that contain no uranium, some of the lead was presumably there when the planet was formed, so the approximate age calculated for deep-sea sediments must be actually a *maximum* age.

Fortunately this approach can be refined. There is a third isotope ($^{204}_{82}Pb$), not formed from uranium or any other decay process, and which is therefore constant in abundance through time. If we had a sample that contained no uranium at the time of the Earth's formation, we could measure the ratios of $^{204}_{82}Pb$ to the other two daughter isotopes of uranium decay ($^{206}_{82}Pb$ and $^{207}_{82}Pb$) and this would give a measure of the content of $^{206}_{82}Pb$ and $^{207}_{82}Pb$ at the time of the Earth's formation. For example, the lead from uranium-free materials has eight times the abundance of $^{206}_{82}Pb$ relative to $^{204}_{82}Pb$ and nine times the abundance of $^{207}_{82}Pb$ relative to $^{204}_{82}Pb$. Some minerals formed in meteorites contain lead but no uranium, and the relative abundance of the three lead isotopes, $^{204}_{82}Pb$, $^{206}_{82}Pb$ and $^{207}_{82}Pb$, can be measured. Since the abundance of $^{204}_{82}Pb$ in the deep-sea sediment from which a maximum age for the Earth was calculated is known, the quantity of the other two isotopes present when the isotopic clock started can be calculated, in the same way that in SAQ 10 you allowed for the presence of some daughter isotope at the time the mineral crystallized. The value calculated from this technique is about 4.6×10^3 Ma. Independent calculations from both of the two uranium decay schemes give the same age, and this is powerful evidence that this must be close to the true age of the Earth. Further confirmation that the Earth and other planetary bodies were created about 4.6×10^3 Ma ago has been provided by age determinations carried out on lunar samples; the oldest Moon rocks have also been found to have an age of 4.6×10^3 Ma. Moreover, virtually all dated meteorites

give ages between 4.4×10^3 Ma and 4.6×10^3 Ma. To understand why the Earth, the Moon and meteorites all give a similar age we must turn to the origin of the Solar System.

SUMMARY OF SECTION 6

1 The oldest ages of intrusive rocks from the Earth's crust are around 4.2×10^3 Ma. These have been determined from uranium decay in zircon crystals.

2 A maximum age for the Earth itself, calculated from uranium decay in deep-sea sediments, is between 6.7×10^3 and 5.5×10^3 Ma.

3 A refined age which allows for the presence of lead isotopes in the Earth at its formation is 4.6×10^3 Ma.

4 Lunar material and meteorites give an age of 4.6×10^3 Ma.

7 THE ORIGIN OF THE SOLAR SYSTEM

The formation of the Earth is intimately tied to that of the Solar System as a whole, for, as you may recall from Unit 2, Section 4.3, there is a remarkable regularity between planetary radii and orbital periods, which suggests that the planets had a common origin. To remind you of the scale and relative sizes of planets within our Solar System, look at Figure 27. The Sun is far and away the largest body, but notice that there are four small inner planets and four large outer ones, followed by Pluto, which is another small planet.

How can this distribution of planets be accounted for? After centuries of painstaking data collection there is still some uncertainty, but, broadly speaking, there are two types of theory:

1 'Uniformitarian' theories, in which the Sun and planets all formed from a spinning cloud, or **nebula**, of gas and dust as the cloud evolved by contraction because of gravitational and other forces.

2 'Catastrophic' theories, in which the Sun was formed before the planets, and the material for the planets came from the Sun or another star in a 'one-off', never-to-be-repeated event.

Before looking at examples of these theories, consider first the evidence that can be used to test their validity.

7.1 CHARACTERISTICS OF THE SOLAR SYSTEM

You may recall from Unit 2, Section 4, that the idea of planets orbiting a central Sun lay dormant from ancient Greek times until the days of Copernicus in the 16th century. After a gestation period lasting about 100 years, Newton finally explained planetary motions mathematically in 1687, using the theory of gravitation to account for Kepler's empirical relationships (see Unit 3, Section 4). Since that time, new planets have been discovered and observations have been considerably refined: Figure 27 and Table 7 contain a synthesis of contemporary knowledge. Any theory for the origin of the Solar System must answer some important questions based on these data:

1 Why do all the planets orbit the Sun in the same direction and more or less in the same plane?

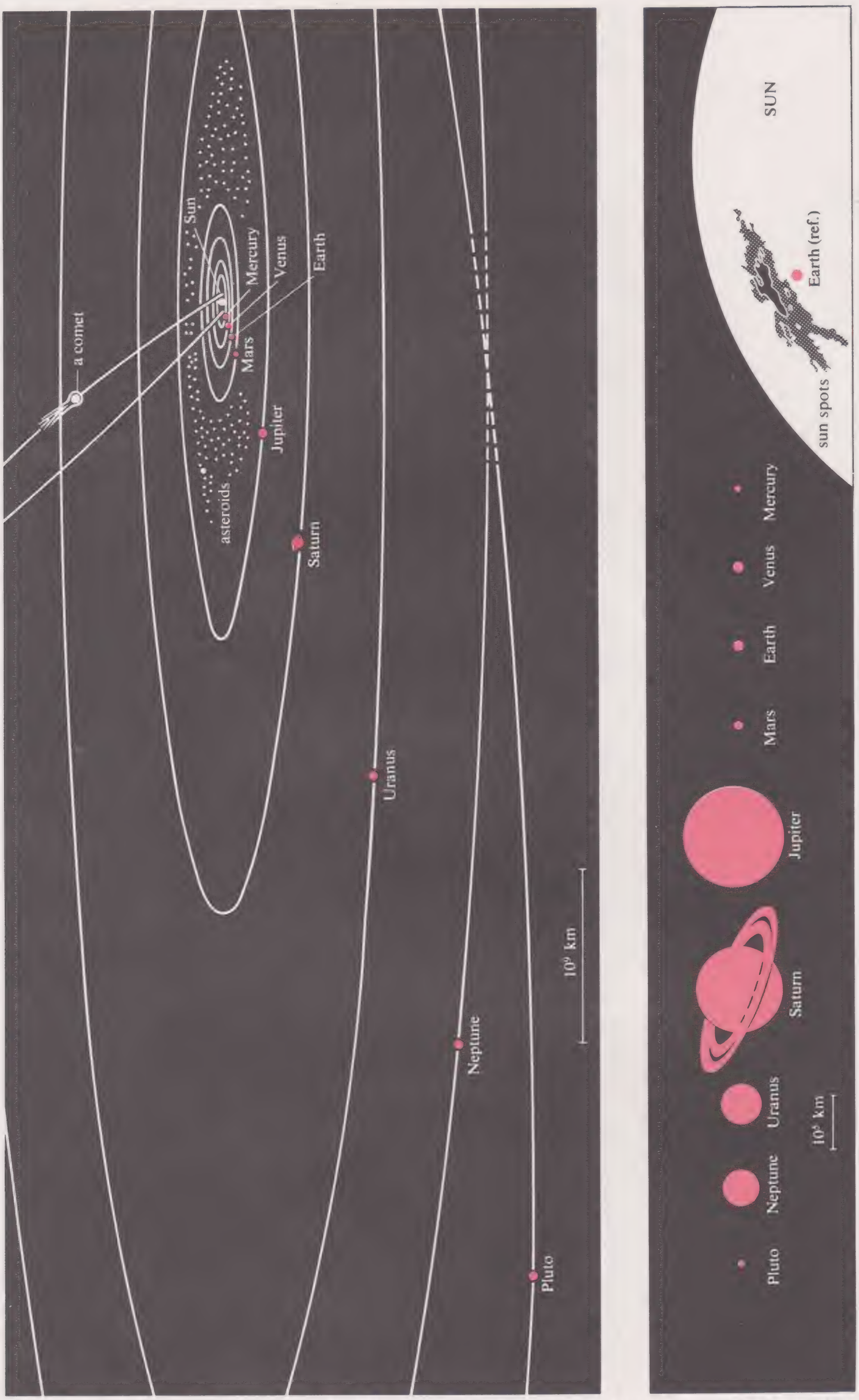


FIGURE 27 A diagrammatic summary of the Solar System, showing how most of the planets orbit the Sun within the same plane as that of the Earth's orbit and also (in the bottom section of the diagram) showing the relative sizes of planets.

TABLE 7 Physical data from Sun, Moon and planets

	Average distance from Sun/AU*	Orbital period/ years	Period of rotation on its axis/days	Radius/ Earth radius ($\approx$ 6 370 km)	Mass/ Earth mass ($\approx 6.0 \times 10^{24}$ kg)	Average density/ $10^3\,kg\,m^{-3}$	Number of satellites
Sun			25.4	109	343 00	1.4	
Mercury	0.39	0.24	58	0.38	0.055	5.42	0
Venus	0.72	0.62	243	0.95	0.815	5.27	0
Earth	1.00	1.00	1.00	1.00	1.00	5.52	1
Mars	1.52	1.88	1.03	0.53	0.108	3.95	2
Jupiter	5.20	11.9	0.41	11.2	318	1.33	16
Saturn	9.54	29.5	0.43	9.5	95	0.69	17
Uranus	19.2	84.0	0.89	3.7	14.6	1.2	15
Neptune	30.1	165	0.53	3.9	17.2	1.7	2
Pluto	39.5	248	6.4	$\approx$0.24	0.002	$\approx$1.3	1
Moon	1.00	0.075	27.3	0.27	0.012	3.33	—

* 1 AU or astronomical unit is the average distance of the Earth from the Sun: 1.496×10^8 km.

ASTEROID

METEORITE

ITQ 13 Now look at Table 7. Can you see a simple relationship between planetary radius and density? Bearing in mind your knowledge of the Earth's interior, is it likely that all planets have similar compositions?

2 Why are the planets divided according to their size, density and chemical composition into two distinct groups? Chemistry is added here because the two ranges of size and density seem to reflect compositional differences. The inner planets (Mercury–Mars) are 'rocky' and so far as has been determined from space missions and remote observations they, like the Earth, are composed of iron-rich silicates. The outer planets (Jupiter–Neptune) are gaseous and 'icy'. Towards the centre, these planets may become liquid or even solid owing to enormous internal pressures, and it is also thought that small cores of inner-planet type may exist at the very centre of the outer planets.

Incidentally, the smaller size of Pluto is not quite so exceptional as it seems at first sight, for the larger outer planets all have moons with widely different densities and sizes; some are even larger than the inner planets. It is quite possible that Pluto is one of these moons, now in orbit around the Sun rather than around its original planet. Alternatively, it may have been captured from outside the Solar System.

Now look at the second column of Table 7, where the average distance of each planet from the Sun is recorded. (The average is given because planetary orbits around the Sun are elliptical.) Notice how the relative distances between successive planets become much greater further from the Sun.

3 But there is a larger gap than normal between Mars and Jupiter. Why is this? On close inspection it turns out that this space is not empty but contains a 'belt' of some 2 000 little 'planets' called **asteroids**. It is thought that they have resulted from the break-up of a single, or several, larger planets that once existed in this region. Asteroids are extremely important in our ideas of the Earth's formation because it is known from the study of the orbits of **meteorites** (rocks of cosmic origin that fall to Earth), that they originate from within the asteroid belt. Apart from a few lunar samples, meteorites are the main extraterrestrial material available for direct study and, what is more, some of them probably represent material from deep within other planets that have broken up; that is, they consist of *material analogous to the Earth's mantle and core*. The average density of meteorites is about $3.5 \times 10^3\,kg\,m^{-3}$ and quite clearly this makes them more akin to inner planets than to outer ones. The evidence from meteorite samples will be considered more fully in Section 8.

4 Why is it that the outer planets, in spite of their huge sizes, are spinning so fast? Look again at Table 7 and this time at column 4, periods of rotation. The Sun rotates on its axis in 25.4 Earth days, whereas the four large

NEBULAR THEORY

CATASTROPHIC-EVENT THEORY

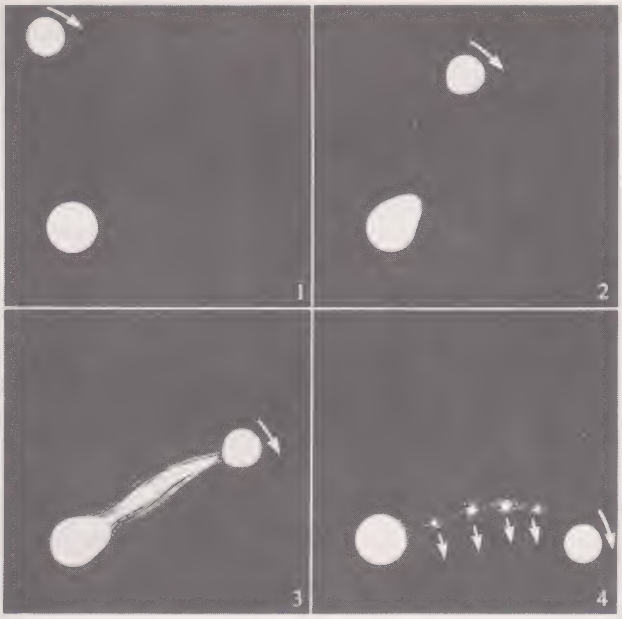
outer planets spin with periods of less than one Earth day. The total amount of spin in the outer planets is quite astonishing compared with the very slow spin of the Sun and the planets nearer to it. So massive are the outer planets too, that they possess much of the kinetic energy of the Solar System. Against this background, in Section 7.2 we shall consider how to account for the origin of the Solar System.

7.2 NEBULAR AND CATASTROPHIC THEORIES

One of the best-known theories for the origin of the Solar System dates from 1796, when the Marquis de Laplace proposed his **nebular theory** (see Figure 28a). This theory is of the evolutionary or uniformitarian type: its central idea is that a flat, disc-shaped rotating cloud of gas and dust (that is, a nebula) gradually contracted and condensed to form the Sun. It is assumed that the entire disc rotated uniformly, so that the speed of motion of particles at the perimeter far exceeded that of particles near to the centre. Eventually, the spinning disc broke up in such a way that a *ring* of nebular material stayed in a steady orbit while the remainder continued contracting under gravity towards the centre. Eventually, conditions prevailed which were suitable for the Sun's 'nuclear reactor' to produce energy in the form of light and heat which arrested the contraction process—a situation, fortunately, which still prevails. Variants of the nebular theory include the development of several regularly spaced rings, as depicted in Figure 28a, each of which aggregated to form a planet.

Although the nebular theory was initially widely accepted as explaining the distribution of planets along one plane through the Sun, and their regular spacing, it ran into difficulties during the 19th century, as more accurate data were collected about the sizes, masses and spins of all the planets. The main problem was that of the periods of spin. Although detailed explanation requires mathematical techniques that are outside the scope of S102, the gist of the problem can be stated very simply. If the Sun and the inner planets resulted from continuing *contraction* of a rotating nebula, they

(a)



(b)

FIGURE 28 (a) Schematic illustration of the nebular theory for the evolution of the Solar System from a rotating nebula that sheds gaseous rings during contraction. These condense to form the planets and their satellites, while the central part continues contracting to form the Sun.

(b) Illustration of the Jeans–Jeffreys catastrophic-event theory. In 1, a condensed star approaches the Sun; in 2, both bodies are tidally distorted as a result of gravitational interaction, leading to 3, in which a filament of gaseous material is torn away from the Sun (or from the other star); in 4, the material condenses to form planets, and the star recedes.

should be spinning *faster* than the outer planets and not the other way round (see Section 7.1). This argument caused evolutionary theories to be abandoned, and catastrophic theories became established by James Jeans and Harold Jeffreys during the early years of the present century. The process is illustrated in Figure 28b and involves the close approach of another condensed star to the Sun. The gravitational forces involved would cause huge tides to be raised on the star and the Sun until a cigar-shaped filament of stellar material became torn away from one or both and condensed between the two stars to form planets. The Jeans–Jeffreys **catastrophic-event theory** overcomes the problem of the variation of planetary spin rates. It is reasonable to expect that the Sun itself would be less affected by the 'turning' pull of the passing star than the loose material, forming planets, which was closer to the star. The idea was well received at first, but a few problems arose during the 1930s and 1940s, when it was realized that stellar material at temperatures exceeding a million °C would be likely to disperse rather than condense into planets! Statistical arguments were also used and some astronomers argued that the chances of a close encounter between two stars are rather low.

Following this state of uncertainty, there have been various attempts to revive both classes of theory during the last 20 years. So far, there is no positive conclusion, and you should appreciate that even after centuries of quite precise observation, scientists are unable to choose one theory for the origin of the Solar System. The important parameter that is so inaccessible to us is *time*. Stars are born and die, perhaps with planetary systems, on time-scales of *tens of millions of years*. Only by the chance discovery of other solar systems in the process of formation would it be possible to probe more directly the mysteries of the process and finally choose the better theory.

SUMMARY OF SECTION 7

1 The four inner planets, Mercury, Venus, Earth and Mars, are relatively small, dense and rocky, whereas four of the outer planets, Jupiter, Saturn, Uranus and Neptune, are large, light and gaseous. The outermost planet, Pluto, is small, but of low density.

2 Meteorites are broken-up remnants of inner planetary material which originate from the asteroid belt, between Mars and Jupiter.

3 The two prominent, contrasting theories for the origin of the Solar System are:

(a) the 'evolutionary' nebular theory;
(b) the catastrophic-event theory.

At present, there is evidence to favour aspects of both theories, but neither has gained unanimous support.

SAQ 13 Which statement in the following list is *wrong*?

A The asteroids are a group of small planetary objects, which are part of the solid, high-density inner-planet group.

B On the basis of density, the outer planets must be composed of silicate mantles and iron cores.

C The axial spin periods of the outer planets are shorter than those of the inner planets.

D The inner planets are relatively small and of high density compared with the outer planets.

E Meteorites are fragments of planetary debris which fall on the Earth and are thought to originate in the asteroid belt.

SAQ 14 What were the principal objections to (a) the nebular theory, and (b) the Jeans–Jeffreys catastrophic-event theory in the period up to 1950?

IRON METEORITE

WIDMANSTÄTTEN PATTERNS

ALLOY

8 PLANET FORMATION AND LAYERING

In Section 6, you learnt that the evidence from uranium and lead isotopes points to an event that affected the Earth, Moon, meteorites and probably all other planets about 4.6×10^3 Ma ago. This is the probable time when the whole Solar System came into being by one of the processes discussed in Section 7.2. It is thought that all the planets began the separation into different layers at about this time, just like the Earth. But *how* did they become layered and what were they like at formation?

□ Start from the end product: what evidence is there that the Earth is layered (see Figure 29), and why, for example, is it thought to have an iron-rich core?

■ From Units 5–6, Section 4, you probably recalled the *seismic evidence*, which reveals the Earth's internal structure and places physical constraints on possible compositions at various depths using density and elastic moduli. But did you remember *iron meteorites* from Units 5–6 (Section 4.4.3)?

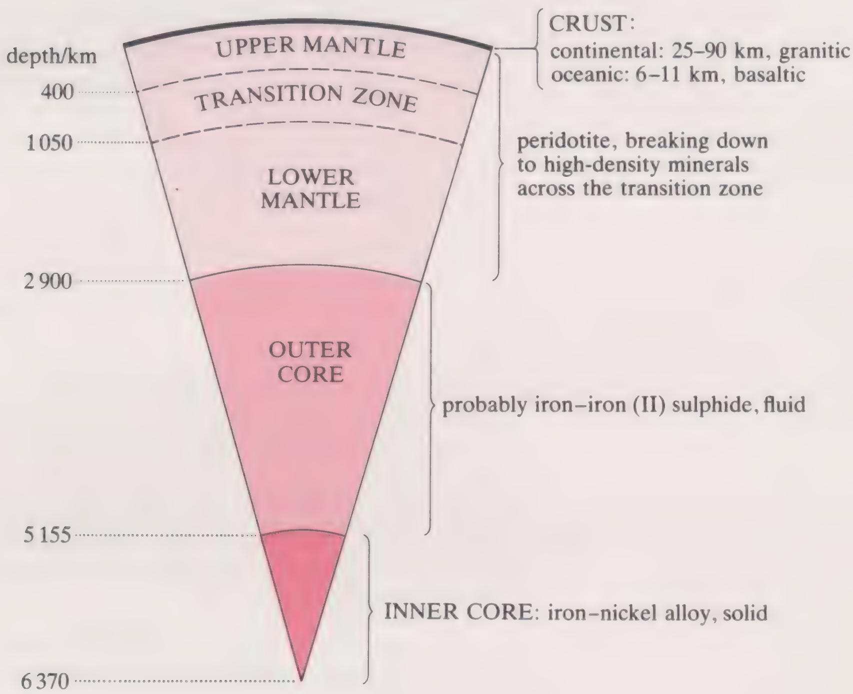


FIGURE 29 Diagram showing the structure and composition of the Earth's interior.

In fact, as you will now see, by far the most useful source of information concerning both the composition of inaccessible terrestrial planetary layers, and about the planets before layering took place, comes from meteorites. On the basis of density alone, these bodies are highly relevant to a study of the inner, Earth-like (or terrestrial) planets (Section 7.1).

8.1 THE EVIDENCE FROM METEORITES

Occasionally, meteorites can be seen passing through the atmosphere, where the vast majority of them burn up completely, but some do survive to reach the Earth's surface. It has been estimated that only about 500 'falls' occur each year over the whole Earth, and of these only about 10 are recovered; in all, about 1 700 known 'falls' have been recorded. The typical fall has a mass of a few kilograms and usually breaks into several fragments before or after impact; very occasionally much larger meteorites reach the Earth and excavate large craters (see Figure 30).

FIGURE 30 A meteorite crater in Arizona, 1 300 m across, 180 m deep and with a rim raised 40 m.

Meteorites are of three types:

(i) **Iron meteorites** (or simply 'irons'; see Figure 31a) These consist of a nickel-iron alloy, typically with 4–20% nickel; often sulphur is also present. Irons are by far the most abundant meteorite 'finds', largely because they are so unlike any terrestrial rocks; but they are believed to form only about 6% of total falls.

Very often these meteorites show a fine structure called **Widmanstätten patterns**, after the Viennese porcelain manufacturer who discovered them (see Figure 31a). The patterns consist of two different iron–nickel **alloys**, whose detailed chemistry can be used to determine the cooling rate of these meteorites. After solidifying from a melt at temperatures of about 1 400 °C, this iron meteorite material separates into two alloys at lower temperatures, one nickel-rich and one nickel-poor. The reason why this occurs is beyond the scope of this Course, but a detailed analysis of the chemistry of Widmanstätten pattern in meteorites, coupled with experimental simulations, has shown that the patterns grew at a cooling rate of between 1 and 10 °C Ma^{-1}. Now you might think this a rather slow rate, but compare it with the much slower cooling rate of the Earth's core (probably around 0.25 °C Ma^{-1}).

(a)

FIGURE 31 (a) Iron meteorite showing Widmanstätten patterns produced by etching the crystals of iron–nickel alloy (polished and etched).

STONY–IRON METEORITE

STONY METEORITE

CHONDRULES

CHONDRITE

ACHONDRITE

CARBONACEOUS CHONDRITE

□ Iron is a metal with a high thermal conductivity (that is, it loses and gains heat comparatively rapidly), and if left floating about in space as small lumps, would cool very much more rapidly than 10 °C Ma^{-1}. Can you think of any explanation for this slower cooling rate? Think about planetary size.

■ Clearly, the situation does not involve lumps of iron floating around freely in space while they cool, nor burial of the iron quite so deeply as in the Earth's core. Somewhere between these extremes, it has been estimated that most iron meteorites were buried beneath an *insulating blanket* of 'mantle' silicates before their *parent planets* broke up to provide a source of meteorite material (Section 7.1). An average of these estimates is 200 km depth of burial.

So iron meteorites are probably core material from small parent planets: these cores were once hot, as the Earth's outer core is molten today. If iron meteorites originate from the *cores* of these parent planets, what happened to the mantles?

(ii) **Stony–iron meteorites** (see Figure 31b) These consist of a background (or matrix) of iron–nickel alloy, surrounding grains or fragments of silicate minerals, mainly the magnesium–iron silicate, olivine. They form about 2% of total falls.

(b)

FIGURE 31
(b) Stony–iron meteorite. High reflectance is shown by polished iron. The inclusions are olivine crystals.

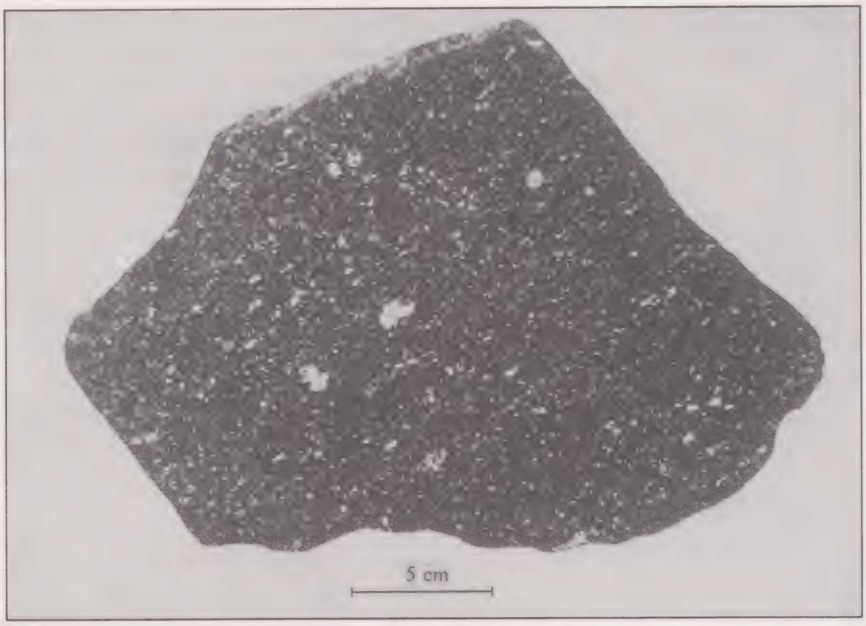
(iii) **Stony meteorites** (or simply 'stones'; see Figure 31c) These form well over 90% of all meteorite falls and most commonly consist of the same minerals that predominate in terrestrial peridotites, namely olivine and pyroxene (Unit 27, Section 3).

About 7% of stony meteorites appear to be homogeneous and composed solely of peridotite. The rest differ from these peridotitic meteorites in two crucial respects:

(a) some nickel–iron alloy and iron(II) sulphide is present;

(b) much of the olivine is present as small rounded spheres or **chondrules***, a few millimetres across (Figure 31c), a feature never found in igneous rocks formed on Earth. The chondrules are usually interpreted as 'droplets', which condensed from incandescent gas during the formation of the parent planets. Even in many of these **chondrites**, as meteorites with chondrules are

* From the Greek *chondros*, meaning grain or seed; the 'ch' is pronounced like 'k'.



(c)

FIGURE 31
(c) Chondritic, stony meteorite. Photomicrograph showing chondrules about 3 mm in diameter set in a silicate matrix (thin section; transmitted light).

called, the chondrules have been partially destroyed by metamorphism (see Unit 27, Section 5) in the temperature range 100–1 000 °C.

The important point to note is that, although most chondrites have been metamorphosed, *none has ever melted*. On the other hand, the small number of peridotitic stones show many signs, both textural and chemical, that they were formed originally from chondritic material by *melting and subsequent crystallization*. These peridotitic meteorites are termed **achondrites**.

ITQ 14 How do we interpret the stony meteorites? If we are looking for remains of planetary *mantles* among them, which type of meteorites seems to be most suitable and why?

So it seems that *iron cores* and *achondrite mantles* were both parts of the same parent planets, perhaps with the material of which the stony–irons are composed forming a diffuse boundary layer between them. Notice also that irons and achondrites are the two meteorite types that have been molten during their histories. As you will see in Section 8.2, melting is a highly efficient process whereby separation of planetary cores and mantles can be effected. By contrast, chondritic meteorites contain the iron, iron(II) sulphide and silicate ingredients of terrestrial planets, and at no time were wholly or partially molten. It is thought that of the many parent planets, only the larger ones—several hundred kilometres in diameter—were able to reach the conditions necessary for separation into core and mantle.

□ Suppose you wanted to examine the composition of the *most primitive unaltered* material that accreted to form the inner terrestrial planets, before they became layered. Which group of meteorites would you use?

■ Chondritic meteorites, because they are the least modified material available (melting and iron/silicate segregation have not taken place).

There is considerable variety of chondrite compositions, and the least altered and metamorphosed are the **carbonaceous chondrites**—so called because they contain a few per cent of carbon and other volatile elements such as sulphur. (Note that if they had been metamorphosed, the carbon would have been lost as CO_2 gas and the sulphur as SO_2 gas.)

The primitive nature of carbonaceous chondrites can be confirmed by comparing their composition with quantitative estimates of the Sun's composition made from spectral observations (Units 11–12, Section 5), and with the average composition of the Earth's crust (Unit 27, Section 2). Unlike the

CHONDRITIC EARTH MODEL

terrestrial planets, the Sun is composed primarily of hydrogen and other gases. However, these gases are ignored in calculating the ratio of the abundance of each of the heavier elements in the solar spectrum to that of the most abundant heavy element, silicon. By convention, ratios are calculated with respect to a million (10^6) silicon atoms for the Sun's atmosphere and also for carbonaceous chondrites and the Earth's crust, as follows:

$$\frac{\text{abundance of element}}{\text{abundance of silicon}} \times 10^6$$

This ratio for a range of elements in the Sun's atmosphere is compared with the ratio for the same elements in carbonaceous chondrites in Figure 32a. If an element has the same abundance relative to silicon, in chondrites and in the Sun's atmosphere, then it plots on the straight line (which represents equal ratios) in the Figure.

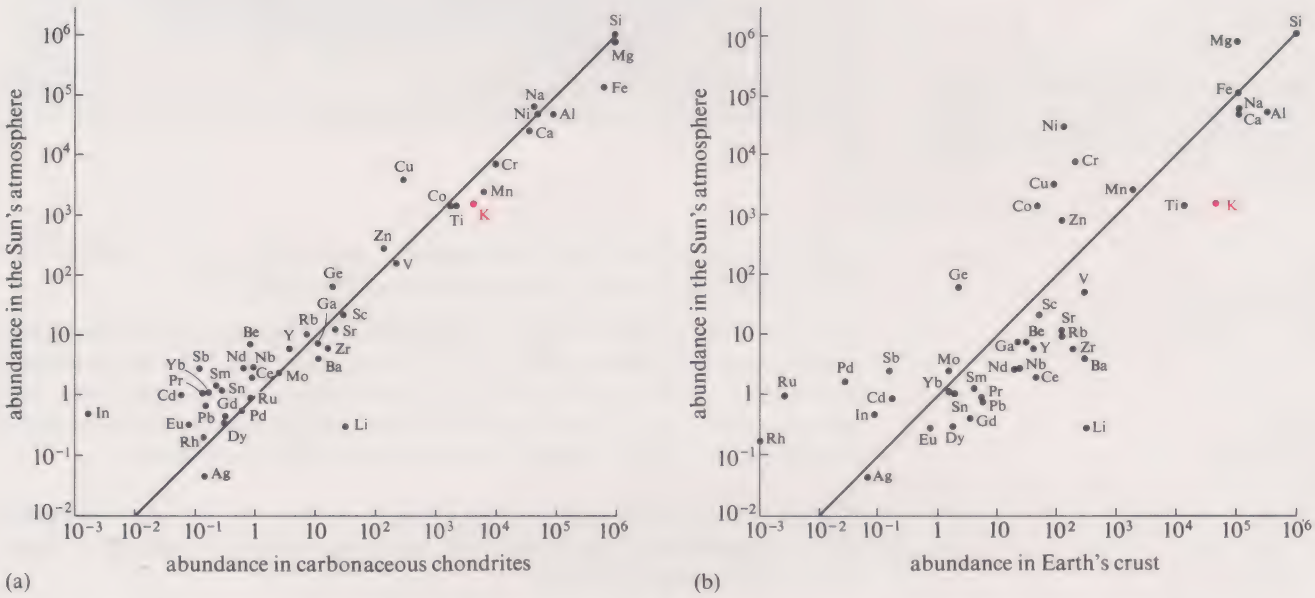


FIGURE 32 Comparison of the abundance of the elements in the Sun's atmosphere with (a) their abundance in carbonaceous chondrites, and (b) their abundance in the Earth's crust. The abundances plotted are the ratios of the number of atoms of each element compared with 10^6 silicon atoms. Thus, for example, there are about 5×10^4 potassium atoms (K) in the Earth's crust for every 10^6 silicon atoms (Si), and about 2×10^3 potassium atoms in the solar atmosphere and carbonaceous chondrites for every 10^6 silicon atoms. Potassium abundances are shown in red.

□ How many elements in Figure 32a show a deviation from this straight line of equal abundance by more than an order of magnitude (that is, by a factor of ten)?

■ None of the more abundant elements (more than 10^3 atoms for every 10^6 silicons), although a few minor elements such as lithium (Li), copper (Cu), indium (In) and antimony (Sb) show significant departures.

In fact, Figure 32a shows a quite remarkable agreement between the heavy-element compositions of the Sun's atmosphere and carbonaceous chondrites, which suggests that *carbonaceous chondrites may be typical of the original Solar System before planet formation*—an extremely significant conclusion. Further support comes from Figure 32b where the same ratios for the solar spectrum are compared with those for the Earth's crust.

□ Which of the more abundant elements (that is, with relative abundance of more than 10^3 atoms for every 10^6 silicons) are most enriched in the Earth's crust relative to the Sun's atmosphere and carbonaceous chondrites, and which are most depleted? Look at Figure 32b and at the elements nickel (Ni) and potassium (K) in particular.

■ Elements such as Al, Ti and K (aluminium, titanium and potassium) are enriched in the Earth's crust because their position on the graph is below the equal-abundance line in Figure 32b, whereas Mg, Cr, Cu, Ni

and Co (magnesium, chromium, copper, nickel and cobalt) are depleted in the crust. The overall 'fit' to the straight line is not nearly so good as that for carbonaceous chondrites.

ITQ 15 Following this line of reasoning to its conclusion, do you think the Earth as a whole might be chondritic? Bear in mind its present structure and probable composition (Figure 29).

So ITQ 15 reiterates the earlier conclusion that terrestrial planets might be chondritic. If the Earth as a whole started with an *overall chondritic composition* and subsequently became layered into a granite–basalt crust, peridotite mantle and a nickel-bearing core, then this would be consistent with the trends noted in Figure 32b. Independently, we have argued for exactly these compositions using seismic data, a knowledge of peridotite melting processes to yield ocean crust (Unit 27, Section 3.3), the evidence of surface rocks, and also the evidence of iron and achondritic meteorites, which are segregated parts of layered planets like the Earth. There seem to have been several meteorite parent planets which, during the last 4 600 Ma, have collided with each other at irregular intervals. They have been broken up, yielding fragments in eccentric orbits around the Sun, and a few of these fragments have fallen to Earth because of the Earth's gravitational attraction. The idea that the Earth is chondritic in composition but that it has been segregated just like the larger meteorite parent planets forms the basis of the **chondritic Earth model**. This model may also apply to all the other inner planets of terrestrial type and will be developed in the context of the Earth in Section 8.2.

8.2 ACCRETION, HEATING AND LAYERING OF THE EARTH AND PLANETS

So far, it has been suggested that the terrestrial planets are chondritic to a first approximation, and Figure 32a suggests that their composition is the same as that of the Sun when the vast bulk of its light gaseous material is excluded. Now let us examine this conclusion more critically, using density data from Table 7. As mentioned in Section 7.1, the outer planets must also contain light elements, but the inner terrestrial planet densities are all greater because of their solid nature, and the small variations present are thought to be due to two factors. The first of these is size, because the larger terrestrial planets, like Earth, will have more compressed and therefore denser material inside compared to the smaller ones.

□ Can you identify the one inner planet that conflicts with this prediction when compared with the Earth?

■ In Table 7, the densities of Mars, Venus and Earth increase in order of increasing planetary size, but Mercury, the smallest planet, has the highest density apart from the Earth.

So we need a second factor to account for the density of Mercury; you might have realized that the composition of this planet must be different to that of the other three. On these grounds, it has been suggested that Mercury has a relatively large iron core and a smaller silicate mantle (iron is more dense than silicates) compared with the other terrestrial planets. Although Mercury is therefore not chondritic, there is no evidence for major differences in composition between Venus, Earth and Mars, all of which may be broadly chondritic. Obviously this is a simplified picture based only on the evidence presented in this Course. There are almost as many speculative, detailed compositions for other planets as there are speculators!

However, you are now in a position to understand how the planets may have accreted. This is an equally speculative process but, for simplicity, let us assume that the Sun was surrounded by a diffuse cloud of a gas and

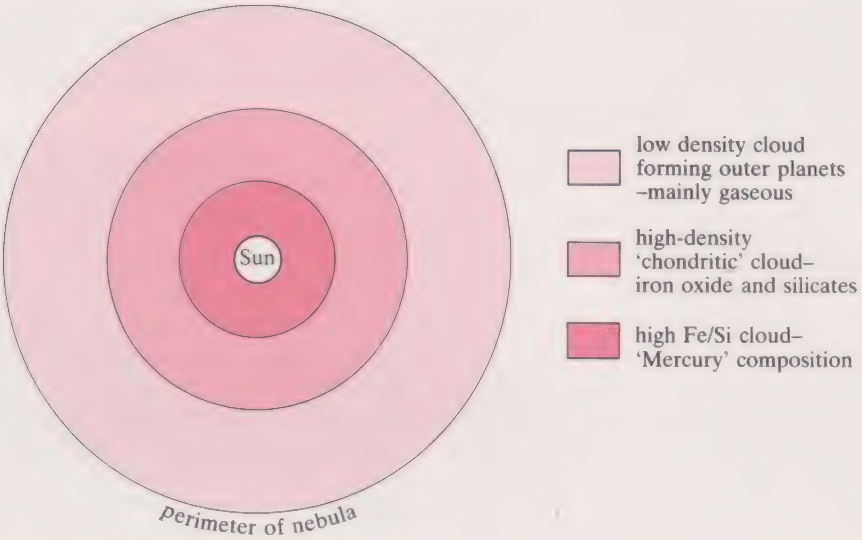


FIGURE 33 Schematic illustration of the possible variations in density of a planetary nebula surrounding the Sun. The variations of density indicated in the diagram reflect the proportions of gaseous and solid materials within the Solar System immediately prior to accretion.

dust, or nebula*, as shown in Figure 33, and let us further assume that the composition of this nebula varied with distance from the Sun as is required by present planetary densities. This could depend on various factors.

Suppose, for example, that temperatures were progressively lower further away from the centre of the nebula. This is not unreasonable if the Sun already had become sufficiently dense to start burning. When heated, the lightest gaseous materials would move more rapidly towards the remote cooler regions, effectively separating these gases from the dense, solid silicates and iron-rich materials closer to the Sun. Other possible factors with similar effects might have been weak magnetic and gravitational forces between the Sun and its enveloping nebular cloud. However, given the picture in Figure 33, the Earth would form within the chondritic cloud. This would also apply to Venus, Mars and the asteroids.

Here, as everywhere within the nebula, random collisions between particles would occur, and the result of such collisions would be the progressive growth and accretion of larger and larger masses, until, eventually, planet-sized bodies would result. During the accretion process, the surface of the Earth probably looked very much like the Moon today. Indeed, following the Apollo missions, we know that many of the lunar surface features have been there since both the Earth and Moon were in their final stages of accretion.

An interesting, and very relevant phenomenon accompanies this progressive growth of planets, for, as their masses became larger, the gravitational attraction for newly accreting particles must have increased.

ITQ 16 What effect would the increase in gravitational attraction have on the impact velocities of new particles, and what would happen to the kinetic energy of these particles on impact?

Estimates have been made on the total heat energy released by accretion, and these extend up to 38×10^6 joules for every kilogram of the Earth. This would supply enough heat to raise the temperature of the whole Earth by 20 000 °C (!) if it happened quickly enough. Of course, if most individual impacts were small, and the process were spread out over millions of years, much of this heat would have been lost into space by radiation. The heating process would have promoted certain chemical reactions. Most significant

* This does not imply that the nebula theory is necessarily preferred to the catastrophic-event theory for the origin of the Solar System. The Sun may equally well have acquired a diffuse cloud by the latter process (Figure 28b).

would have been the reduction of iron from the oxide or silicate of accreting chondrite-like material to the metallic state. We can represent this process by the following equations*:

$$\underset{\text{olivine}}{(Fe, Mg)_2SiO_4} \longrightarrow \underset{\text{pyroxene}}{(Fe, Mg)SiO_3} + \underset{\substack{\text{iron(II)}\\ \text{oxide}}}{FeO} \tag{4}$$

$$2FeO(s) + \underset{\substack{\text{carbon, in}\\ \text{chondrites}}}{C(s)} = 2Fe(s) + CO_2(g) \tag{5}$$

Carbon dioxide gas would be lost into space or the atmosphere (see Section 9), since these reactions would occur near the hot accreting planetary surface. The metallic iron would remain within the planet, eventually to form the principal component of the core.

As the Earth grew, so accretional heating would have become increasingly effective until, eventually, the melting temperatures of some materials would be reached. Now refer to Figure 29 and recall, from this and the back cover of Units 5–6, the compositions of the Earth's inner and outer core. Most of the mass of the core is concentrated in the fluid iron–sulphur outer core; only the inner core is a solid iron–nickel alloy. It turns out that temperatures of only about 990 °C are required for iron–sulphur mixtures to be molten within the surface layer, compared with about 1 550 °C for pure iron and about 1 600 °C for mantle-forming silicates.

At what temperature would planetary layering probably start?

It follows that a stage of planetary accretion and heating (990 °C) would probably be reached at which iron would combine with available chondritic sulphur to form a molten iron/iron(II) sulphide mixture at the surface. Since the density of the iron–sulphur mixture is greater than that of silicates, this melt would sink towards the centre of the Earth, carrying with it any nickel—because of the strong chemical similarity between nickel and iron—to form a core. The net result of this *melting–sinking–core-forming* process was to scavenge the then 'chondritic' planet, draining it of core materials and leaving a silicate or, more precisely, a peridotite mantle. After the core formed, it cooled sufficiently for some iron–nickel alloy to crystallize out and produce a relatively dense solid inner core, leaving a sulphide-enriched liquid outer core—liquid because of the relatively low melting temperature of sulphide mixtures compared with the melting temperature of the metal alloy. Following the separation of the core, the peridotite mantle probably resembled achondritic meteorites and, as in segregated meteorites, the whole process of mantle-core separation probably took place rapidly (in 10^6 to 10^8 years), about 4 600 Ma ago, which represents the isotopic age of the Earth and of virtually all meteorites (see Section 6). Incidentally, at the time of writing, eight meteorites have provided much younger isotopic ages, some of them as young as 180 Ma. Remember that the isotopic age of an igneous rock records the time since it was last a magma. Therefore these young ages indicate that these meteorites are derived from a body which has been volcanically active relatively recently in the history of the Solar System. Many scientists consider these meteorites to represent fragments of Mars, partly because of the abundant evidence of recent volcanic activity on the Martian surface and partly because of the chemical similarities between these meteorites and samples of Martian soil analysed by the Viking mission to Mars.

The Earth was heated primarily by the release of kinetic energy within its own gravitational field. But what has happened since, especially in the mantle?

* Parentheses are used in the formulae of the silicates in Equation 4 because they are of variable composition; the equation is applicable for a whole range of iron : magnesium ratios. This is also why we must use an arrow here rather than the equals sign of the balanced equation.

□ If accretion took only a few tens of millions of years, then the Earth should, by now, have cooled down by conduction and radiation to the point where activity ceases. So why is it still hot enough to sustain molten layers like the outer core and mantle asthenosphere?

■ Another form of heating, which you should recall from Section 4.1, is due to the decay of the long-lived radioactive isotopes of potassium, uranium and thorium.

It is this radioactive heating that drives the lithospheric plates around the Earth's surface and that maintains the asthenosphere as a partially molten, weak layer in the upper mantle. As you should recall from Units 7–8, Section 5.2, and Unit 27, Section 3.3, molten basalt from the asthenosphere is brought to the surface, where it creates the upper layers of the ocean lithosphere, called the oceanic crust. This oceanic lithosphere is resorbed into the mantle at subduction zones, but not without a further partial melting process which creates the magmas that feed the volcanoes of destructive plate margins (Unit 27, Section 3.5). In this way, new continental crust has been created, not all at once like the core, but progressively throughout the geological history of our planet. Crustal growth is driven by, and therefore constrained by, the decay of long-lived radioactive isotopes. However, because the amount of radioactive material present is declining exponentially, this has been at a progressively declining rate.

SUMMARY OF SECTION 8

1 Chondritic meteorites, particularly the carbonaceous chondrites, are thought to represent the closest approach available to the primitive composition of the Earth before it became layered. Their element abundances correspond closely to those of the heavy elements in the atmosphere of the Sun.

2 Achondritic meteorites, comprising silicate minerals only, and iron meteorites, are thought to correspond to mantles and cores, respectively, of meteorite parent planets that heated up sufficiently for an iron-rich melt to form and sink, leaving a solid silicate residue. The properties of the various meteorite types are summarized in Table 8.

3 In an analogous way, the initial Earth probably comprised homogeneous solid material of chondritic composition, which became heated progressively at the surface as the strength of the gravitational field, and hence the kinetic energies of impacting particles increased.

4 Reduction of iron(II) oxide and iron silicates gave rise to the release of CO_2 and the concentration of the iron into metallic and sulphide forms. Once near-surface temperatures achieved about 1 000 °C, molten iron–nickel–sulphur mixtures sank towards the centre to form a core and leave a peridotite mantle. Later, an iron–nickel inner core crystallized from the melt, leaving a molten iron–sulphur outer core.

5 The Earth's core probably formed rapidly right at the beginning of Earth history, this process taking between 10^6 and 10^8 years.

6 By contrast, the Earth's crust has continued growing with time at a rate controlled by the decay of long-lived radioactive isotopes.

TABLE 8 Summary table for meteorites

Meteorite type	Percentage of known falls	Composition	Maximum temperature attained	Probable relationship to parent planet
IRON	6	Fe–Ni alloy (4–40% Ni) WIDMANSTÄTTEN PATTERNS	≈ 1 400 °C	CORE (cooled at 1–10 °C Ma^{-1}, representing approx. 200 km burial beneath a silicate mantle 'blanket'. The Earth's core, has a much thicker mantle, cooling more slowly at about 0.25 °C Ma^{-1})
STONY–IRON	2	olivine in an Fe–Ni alloy matrix	≈ 1 400 °C	CORE–MANTLE BOUNDARY (incomplete separation of mantle and core material)
STONY: ACHONDRITES	7	olivine, pyroxene and some feldspar = composition of undepleted mantle, i.e. mantle that has *not* been partially melted	≈ 1 400 °C	MANTLE
STONY: CHONDRITES	85	variable amounts of silicates + CHONDRULES (condensed silicate droplets—once glassy, now microcrystalline)	0–1 000 °C. metamorphosed but not differentiated	HOMOGENEOUS, UNDIFFERENTIATED PLANETS or the unmelted surface layers of differentiated planets, therefore may be the closest to PRIMITIVE SOLAR NEBULA COMPOSITION)
		CARBONACEOUS chondrites contain a few per cent of C and S	the least heated (less than 200 °C) because the C and S are not lost	

SAQ 15 Which of the following statements about meteorites are correct?

A Both chondritic and achondritic meteorites are classified as stones; together they comprise over 90% of known meteorite falls.

B Iron, achondritic and stony–iron meteorites show evidence of having reached temperatures sufficient to separate them into parent planetary cores, mantles and a diffuse boundary region.

C Chondrules were probably formed during the metamorphism of chondritic meteorites.

D Because the composition of the Earth's core is known to correspond well with that of certain chondritic meteorites, the chondritic Earth model became established.

E The carbonaceous chondrites are recognized as having the most primitive solar composition—unaltered by subsequent processes.

SAQ 16 Consider the development of the following Earth layers:

(a) core;

(b) mantle;

(c) crust.

In terms of our exposition in Section 8, decide in each case, what primary energy source was probably involved in layer formation and how rapidly the layer was developed.

REDBEDS

PYRITE

URANINITE

DETRITAL GRAINS

BANDED IRONSTONE FORMATION

9 EARLY EARTH HISTORY: ORIGIN OF THE ATMOSPHERE AND OCEANS

The crust represents the solid components of the Earth's outer layer which have separated from the mantle by volcanic processes. The atmosphere and the oceans are the gaseous and liquid components of these same processes and consequently have been produced throughout Earth history. However the composition of the atmosphere has changed dramatically with time, and these changes have placed powerful constraints on the evolution of life.

9.1 THE EVIDENCE FOR ATMOSPHERIC OXYGEN LEVELS

TABLE 9 The present composition of the Earth's atmosphere*

Constituent	Abundance/%
N_2	78.08
O_2	20.94
Ar	0.93
CO_2	3.3×10^{-2}
Ne	1.8×10^{-3}
He	5.2×10^{-4}
Kr	1.1×10^{-4}
H_2	5×10^{-5}
N_2O	5×10^{-5}
Xe	10^{-6}

* Concentration of water vapour is variable: 0–3%.

The present composition of the atmosphere (Table 9) is quite simple: it is made up almost entirely of nitrogen (78%) and oxygen (21%). There are minor, but important amounts of water vapour (0–3%), argon (less than 1%) and CO_2 (0.03%), as well as noble gases such as krypton and xenon. Unfortunately, over big cities there is also often much sulphur dioxide as well as oxides of nitrogen formed from motor vehicle exhausts and emissions from power stations. London's atmosphere contains about 1.3×10^{-5}% SO_2, for example. The addition to the atmosphere of these substances and of CO_2 from the burning of fossil fuels may have serious consequences for humanity's future.

At present, however, we are concerned with the evolution and origin of the Earth's atmosphere. What evidence can be used to reconstruct the way in which the atmosphere has developed? How could we tell, in the absence of any fossil remains whether the past atmosphere contained oxygen? The answer proves to be quite simple, for the evidence is found in the nature of the rocks formed at various times in the past.

You may remember from Units 13–14, Section 3, that certain elements like copper can have more than one valency. Iron, for example, exists in nature as either iron(II) or iron(III). The change from iron(II) to iron(III) represents an oxidation reaction since it implies that the iron atoms each lose an electron (Units 17–18, Section 6.3).

□ What effect does exposure to the present-day atmosphere have on iron-bearing minerals and why?

■ Oxygen in the atmosphere reacts with such minerals to convert them into new substances—mainly oxides and, in the presence of water, hydroxides. Most of the iron in igneous rocks is initially present as iron(II). Exposure to the atmosphere can lead to oxidation from iron(II) to iron(III).

As a result, the colour of iron-rich silicates is markedly affected.

□ What colour changes occur when iron-rich silicate minerals are oxidized?

■ The dull or dark colours of the silicates are converted to the rusty yellows, browns and reds of oxides and hydroxides.

Similarly, oxygen in the atmosphere, together with water, reacts with minerals in all rock types to varying degrees to cause decomposition, or breakdown of the original crystal structure (see Unit 27, Sections 4.2 and 4.3). This results in the formation of new minerals, or in the production of dissolved

substances containing Ca^{2+}, Na^{+} and K^{+} ions in groundwater, surface streams and, ultimately, the ocean. This is an important point which will be taken up again later.

So under present atmospheric conditions, iron(II) is easily oxidized on weathering of primary silicate minerals, and the oxide–hydroxide product accumulates in secondary, sedimentary rock environments. Sedimentary rocks containing abundant oxidized iron(III) are called **redbeds** because of their typical colour. Redbeds are usually sand and gravel mixtures that have been deposited under oxygen-rich aerated conditions, for example as river deposits. Now, the crux of the argument is that if we can recognize redbeds occurring in ancient sediments, then it is a fair assumption that sufficient oxygen must have been available in the atmosphere for oxidation to have taken place. Thus, we can gather from the occurrence of redbeds that abundant oxygen was already present when organized life-forms appear in the geological record about 500 Ma ago. But what happened earlier in geological time?

Two other oxygen indicators have proved particularly useful: the presence or absence of the minerals **pyrite** (FeS_2) (Kit sample V) and **uraninite** (U_3O_8). Both dissolve in moist oxidizing conditions to form soluble salts, and so their presence in sediments is taken to suggest a lack of the necessary oxygen.

You are now in a position to appreciate the use of these oxygen indicators for ancient rocks. Some crucial results have come from rocks approaching 3×10^3 Ma old in South Africa called the Witwatersrand System, and in Canada, called the Elliot Lake Group. These strata are hundreds of metres thick and are composed mainly of coarse sediments, predominantly sandstones and conglomerates. They are gold-bearing, river-lain deposits, which were often 'panned' by the ancient prospectors. Together with the grains of heavy gold minerals are the two minerals pyrite and uraninite. These dense mineral grains accumulated in pot-holes and irregularities on the stream bottom because of their tendency for rapid settling compared with fine sand grains: they are referred to as **detrital grains** (that is, original primary mineral fragments, which have been redeposited unchanged into new sediment). If oxygen had been available, there would have been a tendency for these detrital grains to dissolve, and so their presence suggests a dearth of oxygen when their 3×10^3 Ma-old host sediments were deposited.

Further proof lies in the almost complete absence, in the geological record, of redbeds older than about 2.2×10^3 Ma. After this time, redbeds become increasingly abundant and are widespread in younger rocks. Incidentally, prior to this time, any free iron reaching the oceans would have been in the iron(II) state and would have been deposited by living organisms to form a sequence of rocks, common in the early Precambrian, known as **banded ironstone formations** (BIFs for short). We shall discuss these living organisms in Section 10.3. Not surprisingly, BIFs disappear from the record soon after redbeds appear. We can conclude, with some confidence, that iron and uranium remained in the reduced state in the old pre-2.2×10^3 Ma sediments, because before that time the atmosphere contained virtually no oxygen. A change to increasingly oxidizing conditions after this time seems to be indicated.

At this point you should note that these assertions have not gone unchallenged, for there is growing evidence, for example, that detrital uraninite grains are accumulating in some modern sediments. No doubt, this debate will continue for some years to come, but it is probable that until 2.2×10^3 Ma ago, there was insufficient free oxygen in the atmosphere to oxidize surface materials.

If, before this time, the early atmosphere was without oxygen, the question arises as to the origin of atmospheric oxygen and this is the subject of Section 9.2.

BLUE-GREEN BACTERIA

STROMATOLITES

OZONE LAYER

METEORIC WATER

9.2 THE SOURCE OF ATMOSPHERIC OXYGEN: PHOTOSYNTHESIS?

It was during the 1950s that geologists first noticed microscopic structures resembling modern micro-organisms within ancient Precambrian rocks. Techniques were soon developed to analyse these structures, and indeed they were proved to be organic, the fossilized remains of bacteria including **blue-green bacteria** (formerly termed blue-green algae), which have modern living counterparts. Blue-green bacteria are single-celled organisms which lack a well-defined nucleus and reproduce by simple division. The structures produced by modern communities of blue-green bacteria have analogues in ancient rocks: these analogues are called **stromatolites** (see Figure 34). Such fossils have been traced in some of the earliest sedimentary rocks known, over 3×10^3 Ma old, and their presence indicates that life arose quite early in the Earth's history (see Section 10).

FIGURE 34 Precambrian stromatolite structures built up by ancient blue–green bacteria from Montana, USA.

Of great importance to the origin of the atmosphere is the fact that many of these organisms, to judge from their modern counterparts, must have been photosynthesizers; that is, they manufactured their own 'food' from CO_2, water and light, and gave off oxygen as a by-product (Unit 22, Section 2.2). Once oxygen became available in the atmosphere, some of it would have been converted into ozone (O_3), particularly in the upper atmosphere. It is highly significant that the **ozone layer** provides a protective ultraviolet (u.v.) shield around the Earth, because it absorbs electromagnetic radiation from the Sun in the wavelength range 220–300 nm. Such high-energy u.v. radiation is harmful to life because of its damaging effect on DNA.

Before there was abundant free oxygen in the atmosphere (about 1–3% of the present level is probably required to generate a protective ozone layer), there was no protection on the Earth's surface from the harmful u.v. radiation. It is interesting that modern blue-green bacteria are among the most resistant of all organisms to this type of radiation. This is not really surprising, for their ancestors presumably lived and evolved under conditions that would have selected in favour of organisms possessing some form of protection from u.v. radiation. These primitive micro-organisms were apparently locally abundant in surface waters, probably living a few metres beneath the surface to afford the necessary protection from the u.v. radiation, because water also absorbs u.v. radiation. As far as is known, they represent the only common life on Earth for almost 2000 Ma. The reason for this will be discussed in Section 10.3. But can you now see where the build-up of oxygen in the atmosphere might have come from?

ITQ 17 (a) What is the relationship between photosynthesizing micro-organisms and the build-up of atmospheric oxygen?

(b) What relationship exists between the production of ozone in the upper atmosphere, and the development of complex organisms?

So the success of photosynthesizing blue-green bacteria was largely responsible for the progressive enrichment of the atmosphere in oxygen. Moreover, as oxygen levels increased above 1% of the present level, it became feasible for organisms to respire aerobically—a highly significant step, which led to immensely more complex organisms that had been possible with only primitive anaerobic respiration or fermentation (see Section 10.3).

Although the photosynthetic release of oxygen is an obvious source of atmospheric oxygen, there is an alternative explanation for its development. Water vapour in the Earth's atmosphere may be broken down by u.v. radiation from the Sun into oxygen and hydrogen:

$$2H_2O(g) = 2H_2(g) + O_2(g) \tag{6}$$

This effect is most pronounced in the upper atmosphere, and results in oxygen enrichment because hydrogen is preferentially lost from the Earth. This is because lighter molecules, like hydrogen, can escape the Earth's gravitational attraction at lower speeds than can heavier molecules such as oxygen. Although this process of water breakdown by u.v. radiation certainly does occur, its importance in terms of atmospheric oxygen enrichment is unknown. Most scientists believe that this process could only account for a few per cent of the present amount of atmospheric oxygen, but that it may have been relatively more important earlier in Earth history, before the development of organisms able to engage in photosynthesis.

9.3 VOLCANIC GASES IN THE ATMOSPHERE

An obvious source of gas in the atmosphere is volcanic emission (Figure 35), since lava and ash eruptions are accompanied by great clouds of gas. Even after solidification, volcanic rocks contain some 1% to 2% per cent by weight of trapped gas. It is instructive, therefore, to analyse this gas for its constituents and also to analyse the gas being emitted by active volcanoes (Table 10), and compare these results with the composition of the atmosphere (column 5 in the Table).

Notice from Table 10 that the most important volcanic gas is water vapour, but most of this is often **meteoric**, that is, rainwater trapped in pore spaces in rocks beneath the surface and vaporized by the hot magma at depth.

TABLE 10 The composition of gases emitted by some typical active volcanoes and from solidified lava*

Constituent	Gases from active Hawaiian volcanoes/%	Gases from basalt lava/%	Gases from andesite lava/%	Abundance† in atmosphere/%
H_2O	73.5	83.1	92.9	0–3
CO_2	11.8	8.1	2.0	0.03
N_2	4.7	2.0	1.2	78.08
SO_2	6.6	1.1	0.2	—
SO_3	2.3	—	—	—
F_2	—	3.8	2.3	—
CO	0.5	0.2	0.5	—
H_2	0.4	1.2	0.4	—
Cl_2	0.05	0.5	0.5	—
Ar	0.2	<0.1‡	<0.1	0.93
O_2	—	—	—	20.94

* Bromine and helium are usually also recorded in trace quantities.
† These data come from Table 9.
‡ The symbol $<$ is commonly used for 'less than'.

FIGURE 35 Eruption of the volcano Vesuvius, near Naples, Italy, showing the vast quantities of gas that accompany lava and/or ash emissions.

However, magmas do give off some water vapour not previously exposed at the Earth's surface. Next in importance in volcanic gas is usually carbon dioxide. Other abundant gases are nitrogen, oxides of sulphur, and minor amounts of toxic substances involving fluorine and chlorine (which often occur as HF and HCl). Clearly, volcanic eruptions could be regarded as a source of 'natural pollution', yet studies indicate that, in recent times, this pollution is quantitatively much less important than that produced by the human activity of fossil-fuel burning!

ITQ 18 Bearing in mind that most of the water emitted from volcanoes ends up in the oceans and that soluble compounds of carbon, sulphur, chlorine and fluorine will suffer the same fate, which atmospheric gas is most noticeably absent from the volcanic list? Why do you think this should be? Use the data in Table 10.

Look again at Table 10. You should now recognize that, after volcanic emission, SO_2, SO_3 and Cl_2 are rapidly depleted in the atmosphere since they dissolve in seawater. Earlier, you learnt that the light gas H_2 is depleted by loss from the atmosphere. The gas CO is oxidized to CO_2 and, as you will find in Sections 9.4 and 9.5, much of this also passes into seawater at the present day, although the extent to which this occurred in early Earth history is much less certain. Little fluorine seems to be erupted, although it is present in rock-gases extracted from solidified lava. This leaves the least reactive volcanic gases N_2 and Ar, which, together with oxygen, comprise approximately 99.95% of the atmosphere. Hence a plausible source of atmospheric N_2 and Ar is from volcanic emission.

9.4 THE ORIGIN AND EVOLUTION OF THE ATMOSPHERE

By appealing to volcanic emission, it is possible to account for all the gases of the Earth's atmosphere except oxygen but including the noble gases and CO_2 of Table 9. Remember that oxygen is released into the atmosphere by the photochemical dissociation of water vapour and the photosynthetic release from CO_2 during carbon fixation by micro-organisms.

Entirely consistent with these processes of oxygen release is the geological evidence for the progressive increase in atmospheric oxygen levels throughout Precambrian time (Section 9.1). Despite this consistency, some geologists have argued that the Earth once had a pre-volcanic or primary atmosphere. According to this hypothesis, the terrestrial planets may, like the outer planets, have accumulated an envelope of hydrogen, helium, methane, ammonia and carbon dioxide. It is argued that the lightest gases, particularly hydrogen and possibly helium, would have been rapidly lost, leaving CH_4, NH_3 and CO_2. However, comparisons of the spectra of outer planetary atmospheres with Table 9 have shown that much *larger* abundances of heavy inert gases such as krypton and xenon should be present if this primary atmosphere had been retained. For this reason, it is thought that if there ever had been such a primary atmosphere on Earth, it must have been lost; the present atmosphere originated by volcanic emission.

However, the processes of planetary accretion and heating described in Section 8.2 suggest that, during early core formation, volcanic emission would have commenced with the liberation of CO_2 (see Equation 5, Section 8.2), probably accompanied by H_2O and SO_2. The latter gases would have arisen as products of the reduction of iron(II) oxide by hydrogen and sulphur (derived from the minerals that accreted to form the Earth). So the volatile materials of a chondritic Earth (compounds of carbon, hydrogen and sulphur) would have been liberated, just as lesser quantities are liberated today by volcanic activity (Table 10). Subsequent additions by volcanic activity depend for their energy source on the long-term radioactive heating of the Earth.

□ Given your knowledge of surface sediments in Precambrian times (Section 9.1), can you say anything about the *rate* at which oxygen must have accumulated in the atmosphere?

■ The rate of atmospheric oxygen accumulation must have been very slow at first; any oxygen produced would have been used up in the oxidation of surface materials and any reduced volcanic gases. Some would also have become dissolved in surface waters. The appearance of redbeds at 2.2×10^3 Ma ago suggests that not until this time was there a significant amount of atmospheric oxygen.

As for the other gases, it is probable that a rapid build-up of N_2, Ar, CO_2 and H_2O (forming surface waters) occurred, to judge from the extreme intensity of igneous processes recorded in the early Precambrian record. As you know from the exponential decay of radioactive isotopes (Section 4.2), the 'heat engine' must have been much more vigorous in earlier times. Calculations based on decay rates indicate that the rate of heat production 3.3×10^3 Ma ago was at least seven times greater than at present. Because the rates of volcanic processes are linked to radioactive heat production, it seems likely that in the first 10^3 Ma of Earth history much more volcanic emission took place than at present. Therefore, we may conclude that atmospheric gases have accumulated at an exponentially decreasing rate during the Earth's history, except for oxygen, which only appeared in major quantities after some 2×10^3 Ma had passed. Its appearance heralded a long process of atmospheric and biological evolution, which has resulted in the present atmosphere and diversity of oxygen-dependent life-forms. During the passage of time from 2.2×10^3 Ma ago to the beginning of the Devonian Period, about just 410 Ma ago, the atmospheric oxygen content

HYDROSPHERE

was increasing owing to photosynthesis by marine organisms. But about 410 Ma ago, a major step in the process of biological evolution took place, when plant and animal life emerged onto land (see also Section 10.4).

ITQ 19 Can you think of one reason why this evolutionary step became possible by Devonian times but not before? You may need to recall why early Precambrian life evolved in an aqueous environment.

Once life had emerged onto land, the large land plants of the Carboniferous evolved and greatly increased the rate of photosynthesis. During the formation of the great Carboniferous tropical forests some 290 Ma ago, there may have been more oxygen in the atmosphere than at present! These forests decayed to produce the coal and gas deposits now actively exploited. More recent coal deposits are known, some of great thickness, but the end of the Carboniferous coal sequence has been linked to the onset of a worldwide glacial period (see also Section 11). During the last 270 Ma, the atmosphere has continued to evolve through its relationship with the **hydrosphere** (the total body of water including oceans, rivers and lakes) and with living organisms. In the recent past, as a result of human combustion of the fossil fuels, which took hundreds of millions of years to accumulate, the amounts of CO_2, SO_2 and oxides of nitrogen in the system have all increased.

Apart from volcanic emission, which has become less prominent throughout Earth history, the story of atmospheric evolution is largely one of carbon and oxygen equilibria. The links between the atmosphere and living organisms have been developed in the preceding pages, but the importance of the hydrosphere has not been fully explained. In Section 9.3 and Tables 9 and 10 you saw that CO_2 is an abundant volcanic gas, which amounts to only 0.03% of the present atmosphere. CO_2 is removed from the atmosphere by two processes: (a) photosynthesis, and (b) solution in seawater.

□ During photosynthesis, carbon is fixed into living tissues and thereafter in fossilized carbon remains, and so is removed from the atmosphere–hydrosphere system. Can you think of another way in which the CO_2 dissolved in seawater is removed ultimately from the same system?

■ The answer lies in sedimentary rocks, principally limestones, which are essentially calcium carbonate, $CaCO_3$. In addition to carbon fixation into fossil fuels via photosynthesis, vast quantities of CO_2 from volcanic emissions have become trapped into sedimentary rocks, mainly by biological precipitation from seawater. (Of course, this latter process, involving the secretion of carbonate-rich material, merely removes CO_2 from the system and does not affect the oxygen content.)

At present the oceans contain enormous amounts of CO_2 in solution, mainly as $HCO_3^-(aq)$ and much more is tied up in limestones. Looking at the record of sedimentary rocks, it is interesting to note that carbonates did not become abundant until nearly 2×10^3 Ma ago, although calcareous stromatolites (Figure 34) as old as 3×10^3 Ma are known. Carbonate sediments became increasingly abundant in more recent geological history, and it seems that there is a strong link between their occurrence and the availability of marine organisms, such as blue-green bacteria, capable of removing $CaCO_3$ from seawater and fixing it in limestone. So, in addition to volcanic emission, the atmosphere has evolved through the fixation of carbonate in limestone and carbon in fossil fuels, both reducing the levels of CO_2 in the atmosphere, and the latter producing atmospheric oxygen. Figure 36 summarizes the geological evidence from sedimentary rocks and life-forms which influenced this evolution. We shall discuss the relationship between the evolution of the atmosphere and of life in Section 10.

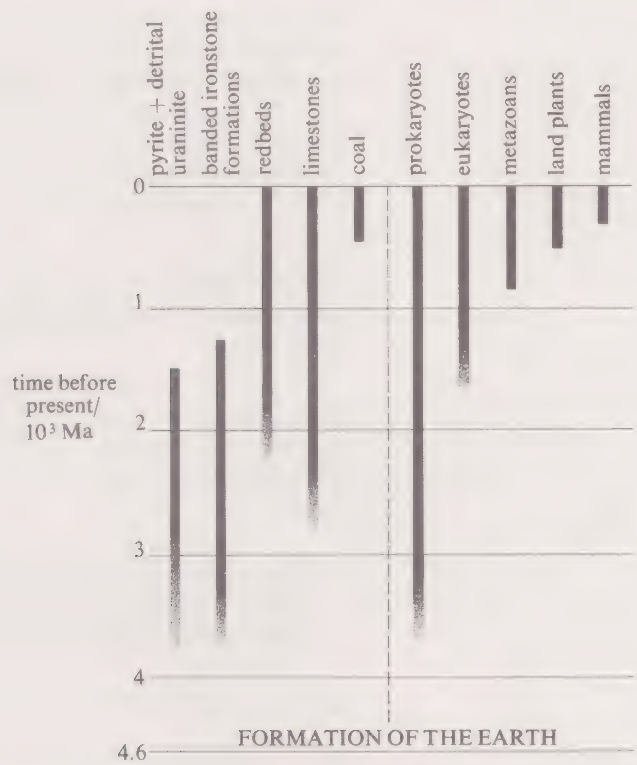


FIGURE 36 Key items in the geological record. The left half of the diagram shows the distribution in the record of some key rock types (Section 9), and the right half of the diagram shows the evolution from lower to higher forms of life (Section 10). The faded bands indicate uncertainty in the placing of limits.

9.5 THE OCEANS

Let us consider first the present-day composition of the oceans. They consist, on average, of 96.7% water and 3.3% of dissolved substances (Table 11). Notice that the elements chlorine and sodium alone make up about 90% of the dissolved matter in seawater. What then is the most abundant salt formed when seawater is evaporated? NaCl, of course. In fact, past evaporation of seawater in enclosed basins has led to the formation of the world's common salt deposits.

TABLE 11 Concentration of elements dissolved in seawater (a) and in the Earth's crust (b)

(a)	Concentration in seawater/% by mass	(b)	Concentration in Earth's crust/% by mass
chlorine	1.900	oxygen	46.60
sodium	1.060	silicon	27.70
magnesium	0.127	aluminium	8.13
sulphur	0.088	iron	5.00
calcium	0.040	calcium	3.63
potassium	0.038	sodium	2.83
bromine	0.007	potassium	2.59
carbon	0.003	magnesium	2.09
strontium	0.001	titanium	0.44

By comparing parts (a) and (b) of Table 11, it is obvious that some elements are common in both seawater and the Earth's crust, whereas others have markedly different abundances.

☐ Which are the four most abundant elements found in seawater that are not among the nine most abundant elements in the Earth's crust?

■ In order of decreasing abundance, these are chlorine, sulphur, bromine and carbon.

Notice that the concentrations of sodium, magnesium, calcium, potassium and strontium in seawater can be accounted for by the process of rock weathering mentioned in Section 9.1 of this Unit and described in detail in Unit 27, Section 4.2. Salts of these metals are the most soluble products of chemical weathering of primary rocks; they are carried by rivers to the oceans. But we must appeal to other sources for the origin of chlorine, sulphur, bromine and carbon.

ITQ 20 Bearing in mind the earlier discussion of the origin of the atmosphere, can you think of a possible source for these four dissolved elements in seawater?

So the dissolved substances in seawater have a mixed origin. It is interesting that the two elements that together make the sea salty have completely different origins: sodium from continental erosion and chlorine from volcanoes.

□ Can you suggest why the concentration of carbon is much lower than that of chlorine and sulphur (Table 11), when carbon dioxide is a much more abundant volcanic gas than chlorine and sulphur dioxide (Table 10)?

■ The equilibrium between carbon dioxide and water is given by

$$CO_2(g) + H_2O(l) \rightleftharpoons H^+(aq) + HCO_3^-(aq) \qquad (7)$$

Similar equilibria exist for sulphur dioxide and chlorine:

$$2SO_2(g) + 2H_2O(l) + O_2(g) \rightleftharpoons 4H^+(aq) + 2SO_4^{2-}(aq) \qquad (8)$$

$$Cl_2(g) + H_2O(l) \rightleftharpoons 2H^+(aq) + OCl^-(aq) + Cl^-(aq) \qquad (9)$$

As you saw in the chemistry experiment at Summer School, when a solution contains a mixture of ions it is necessary to look at all possible combinations of anions and cations and to have some information about the relative solubilities of those salts in order to be able to predict which one is likely to be precipitated first. At the concentrations prevailing in seawater, calcium carbonate is the salt that is selectively precipitated; the carbon dioxide of the atmosphere is biologically fixed as limestone via solution in seawater. The most likely sulphate to be precipitated is also the calcium salt, but some evaporation of seawater is necessary (that is, the concentration of the ions must increase) before this can occur. However, before any calcium chloride can be precipitated, exceptional conditions of extreme evaporation (such as are found today in the Dead Sea) are required. In seawater, therefore, the ranking order of abundance is the inverse of that in volcanic gases as a result of the relative solubilities of the calcium salts of the anions derived from Equations 7 to 9.

SUMMARY OF SECTION 9

1 The Earth's early atmosphere was reducing: it comprised water vapour, nitrogen, carbon dioxide and argon, possibly with methane and ammonia. The first four gases are of volcanic origin and their atmospheric concentrations have been augmented, but at an ever-decreasing rate, throughout the Earth's history.

2 Sandstones, conglomerates and banded ironstone formations older than about 2.2×10^3 Ma contained incompletely oxidized iron and uranium-bearing minerals, indicating a paucity of atmospheric oxygen. After this time, the iron in such sedimentary rocks occurs in the oxidized form (Figure 36), indicating the presence of significant amounts of oxygen in the atmosphere.

3 Atmospheric oxygen has accumulated progressively by two processes:

(a) photochemical dissociation of water;

(b) photosynthesis by blue-green bacteria and, during the last 400 Ma, by land plants.

The latter process removes CO_2 from the atmosphere–hydrosphere system by fixing carbon into plant material and has become more important with time.

4 Ocean water has also been produced by volcanic emission and condensation. It was present at least 3.5×10^3 Ma ago, to judge from ancient water-lain sediments of this age.

5 Modern seawater contains about 3.3% dissolved matter—a mixture of soluble continental weathering products (K, Na, Ca and Mg) and the more reactive volcanically emitted elements (chlorine and bromine as ions, sulphur as sulphate ions, carbon as bicarbonate ions). The concentrations of aqueous ions in the oceans has increased throughout most of geological time.

6 In addition to photosynthesis (3b above), CO_2 has been removed from the atmosphere by solution in seawater and limestone formation. Few limestones older than 3×10^3 Ma have been recorded; before this time the oceans may have contained more bicarbonate but less calcium, and so have been more acidic.

SAQ 17 Which three of the following statements are *false*?

A Early (pre-2×10^3 Ma) sedimentary rocks contain relatively large quantities of minerals such as pyrite and uraninite, which contain metals in reduced forms.

B The presence of detrital pyrite in stream sediments is evidence for an oxidizing atmosphere.

C The origin of redbeds is related to the oxidation of iron in aerated sedimentary environments.

D Throughout the whole of the Earth's history, carbon dioxide has been extracted from the atmosphere to form limestone and coal.

E Stromatolites are structures recognized in ancient sediments as being due to the development of blue-green bacterial colonies.

F In early Precambrian times, before the Earth's ozone layer was fully developed, oxygen may have been liberated into the atmosphere by photochemical dissociation of water vapour by u.v. radiation.

G Meteoric water is the contribution to ocean water that arose from meteorites.

SAQ 18 Which of the following processes (a) increase, (b) decrease, (c) leave unchanged the carbon dioxide content of the atmosphere? Explain your answers.

(i) photosynthesis by marine organisms such as blue-green bacteria;
(ii) precipitation of limestone;
(iii) photochemical dissociation of water vapour;
(iv) combustion of coal;
(v) the growth of tropical forests;
(vi) development of the ozone layer;
(vii) emissions from typical basalt volcanoes;
(viii) radioactive decay processes;
(ix) the evolution of large land animals such as dinosaurs.

PROKARYOTE

HAEMATITE

CHERT

10 THE ORIGIN OF LIFE ON EARTH

Ever since early civilization began, people have been intrigued by the origin of life. Initial theories invoked special creation in which it was assumed that all our present-day forms were created spontaneously or by an 'act of creation' and have not changed with time: maggots were thought to have been created out of rotting meat, and mice from mildewing hay!

But, as you know from Section 2.4, modern theories of evolution have now been applied to most of the fossil record. Today, zoologists, botanists and biochemists work together with scientists of all disciplines, tracing back the earliest forms of life preserved in rocks and experimentally simulating the primitive Earth conditions in which this early life developed. Geochemists have discovered complex organic compounds in certain meteorites, which provide possible building blocks for the origin of life on Earth. However, the evolution of early organisms must have been intimately linked with the evolution of the Earth's atmosphere and oceans. For this reason, the next few pages look at the early evolution of life in a little more detail.

10.1 LIFE AND THE EARTH'S EARLY ATMOSPHERE

Before starting this story, you should be clear that all living organisms are endlessly varied permutations of water, carbohydrates, fats, adenosine phosphates (ADP and ATP), proteins and nucleic acids (Units 22 and 23). The difference between such organic molecules and living organisms is that the latter are able to reproduce themselves by means of a genetic code; that is, living organisms are able to convert non-living material into part of a living system. Living organisms can also become adapted to changes in their external environment. For life to have originated well over 3 000 Ma ago, it is essential that six basic chemical elements on which all living matter depends were sufficiently abundant in the Earth's surface environment. These elements are carbon, hydrogen, oxygen, nitrogen, phosphorus and calcium.

Analyses of planetary and solar atmospheric spectra, together with direct chemical analyses of carbon-bearing meteorites (Sections 7 and 8), tell us that all six elements are abundant in the Solar System. All six elements are present at the surface of the Earth today (see Table 11, in which phosphorus narrowly misses inclusion). Although the hydrosphere–atmosphere system has provided a reservoir of these elements throughout geological time, you know from Section 9 that little free oxygen was available when life started to evolve. Yet it is equally evident that almost all living organisms today *depend* on oxygen for their survival, so how could life have evolved in an oxygen-free atmosphere? It may seem paradoxical, but the simplest organic molecules, such as methane and ammonia, and the more complex nucleic acids are stable indefinitely only *under reducing conditions*. They are oxidized (albeit very slowly in the absence of a catalyst) when oxygen is present. So the synthesis of the basic organic building blocks could have taken place only when conditions were reducing! You will see shortly that the development of higher forms of life required oxidizing conditions, and so we have a unique set of circumstances whereby the atmosphere and living organisms evolved in parallel.

As you know from Stanley Miller's experiments of 1953 (Units 17–18, Section 8.1) and their subsequent refinements, very complex organic molecules (amino acids and nucleic acids) can be produced from early atmospheric gas mixtures. Such molecules would have become progressively concentrated in the oceans by rainfall to provide the source of nutrients for the first living organisms which developed from the same giant molecules. But the synthesis of giant molecules required an energy source: most likely, this would have some combination of lightning, as simulated in the Miller experiments, and u.v. radiation from the Sun.

□ Can you see that this raises another apparent paradox with regard to the early development of life?

■ We know today that concentrated doses of u.v. radiation are harmful to life, so how could life have evolved in the presence of radiation that would have killed it?

The paradox is the reason why we think that life originated in shallow water, not much more than 10 m deep: sufficiently deep to filter out the deadly u.v. radiation but not deep enough to prevent lower-energy radiation from penetrating to provide an energy source for photosynthesis.

10.2 THE EVOLUTION OF EARLY LIFE

The next stage, the development of giant molecules into living cells capable of feeding on the remaining organic nutrients and capable of self-reproduction, is not yet understood and is therefore difficult to explain. However, one thing is fairly certain: at some stage cells must have developed the ability to produce *their own* food supply. First of all, this would have been through fermentation, but later, solar energy would have been used for photosynthesis. They also developed the ability to undergo simple reproduction by cell division. Such autotrophic (that is, self-feeding; see Unit 22, Section 2.2) organisms could have been similar to some of the blue-green bacteria that are found today. They were certainly **prokaryotes** and would have consisted of single cells or short chains of cells, each cell being independent of all others, and lacking membrane-bound organelles such as mitochondria, chloroplasts and a nucleus. As we found in Section 9.2, these prokaryotic organisms are believed to have been well developed by about 3×10^3 Ma before the present (see also Figure 36), and examples dating back to 3.4×10^3 Ma have been found as fossils.

Now some of the prokaryotes, particularly the blue-green bacteria, had the ability to produce oxygen photosynthetically. Here arises a further paradox, because oxygen, essential for the respiration of many contemporary organisms, would have been toxic to early prokaryotes that had not developed oxygen-mediating enzymes. Their survival therefore depended on their ability to dispose harmlessly of the oxygen through their bodies. This is where the banded ironstone formations, mentioned in Section 9.1 assume critical importance. These comprised alternate layers of **haematite** (Fe_2O_3) and **chert** (biochemically precipitated, fine-grained amorphous silica), often with abundant bacterial remains (Figure 37). It seems likely that any

FIGURE 37 A slab of banded ironstone from early Precambrian rocks of the Mesalic Range, Minnesota, USA. Light-coloured bands are chert (SiO_2) and darker bands are haematite (Fe_2O_3). In most cases both compounds are likely to have been biogenically precipitated from seawater as described for Fe_2O_3 in the text.

EUKARYOTE

METAZOA

EDIACARAN FAUNA

soluble iron(II) transported into the early Precambrian oceans acted as an acceptor for biologically produced oxygen, resulting in the precipitation of Fe_2O_3. The banding suggests a balance between the photosynthetic oxygen-producing prokaryotes and the supply of iron(II) in the immediate environment. Notice too, from Figure 36, how the earliest prokaryotes seem to narrowly postdate the earliest banded ironstone formations (BIFs).

Once prokaryotes had developed oxygen-mediating enzymes, their evolution would no longer have been restricted by the supply of iron(II). They would then have spread rapidly in the oceans, producing excess oxygen which escaped into the atmosphere. In fact, the disappearance of BIFs from the geological record and the gradual introduction of redbeds (the product of atmospheric oxidation; see Section 9.1 and Figure 36) around 2×10^3 Ma ago may be the evidence for this step in evolution. As the atmospheric oxygen levels increased, it became possible for organisms to use oxygen directly in respiration. Indeed, some organisms alive today can change over from anaerobic to aerobic metabolism. This was first demonstrated over a century ago by Louis Pasteur. He found that when the oxygen level of the environment reached 1% of the present-day level, certain bacteria changed from anaerobic respiration to aerobic metabolism, involving the uptake of O_2. There is also evidence that suggests that eukaryotic cells, similar to those found in higher plants and animals today, evolved soon after this period, even though atmospheric oxygen levels may still have been low. You should recall that **eukaryotes** are characterized by cells with a visible nucleus and organelles such as mitochondria.

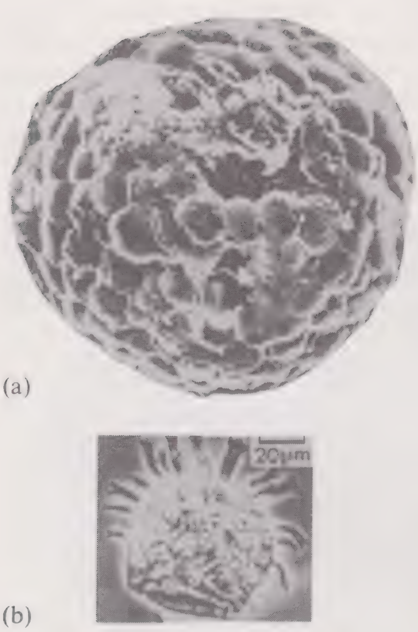
It is interesting to consider why, despite these ancient origins, prokaryotic cell types have very little morphological diversity today. Bacterial cells can produce new biochemical types (for example, new strains of disease) very quickly, mainly because so many cells are produced in a short time and mutations can arise naturally in spite of the fact that most reproduction is by simple fission. However, the eukaryotic cell seems to incorporate a much greater potential for gradual evolution. Important steps that probably provided additional impetus for evolution included: the widespread development of aerobic ecosystems based on the photosynthetic activities of autotrophs, which obtain energy from sunlight (Units 22 and 25), the development of sexuality and the potential for recombination of chromosomes and multicellularity, which probably led to increase of size followed by specialization of cells and tissues.

As evolution progressed, so arose the differentiated, multicellular animals (the **Metazoa**) and multicellular plants, which include the immense diversity of modern life-forms. Although there are some contemporary doubts about how to interpret the geological evidence, this development has traditionally been tied to a critical atmospheric oxygen level—about 3–6% of the present level.

What can be learnt from the fossil evidence about the timing of biological evolution? We shall consider this question in Section 10.3.

10.3 LIFE IN THE PRECAMBRIAN

Until the early 1950s, Precambrian fossils (that is, fossils older than about 600 Ma) were unknown. Yet the earliest Cambrian rocks contain well-developed and complex marine faunas representing many of the modern phyla. In fact by about 400 Ma ago, all of today's phyla are represented in the fossil record. As far back as the time of Charles Darwin, it had been suggested that a long period of evolution must have preceded that first appearance of fossil shells in the Cambrian, but it was not until the 1950s that the universally accepted assemblages of Precambrian fossils were described. These were different kinds of prokaryotic cell from the Gunflint cherts, a 2 000 Ma-old banded ironstone formation from the northern shore of Lake Superior in Canada (see Figure 38).



(a)

(b)

FIGURE 38 Early prokaryotic micro-organisms from Precambrian rocks of Australia (a) and 500 Ma old eukaryotes from the USSR (b). The relative complexity of cell structure increases from prokaryotes to eukaryotes.

Today, approximately 40 different Precambrian assemblages of microscopic plants and bacteria are known, spanning all Precambrian time from 3.4×10^3 Ma before the present. Some of the oldest prokaryotic cells come from the Fig Tree cherts of Zimbabwe. There is even older *indirect* evidence of Precambrian life in some ancient metamorphosed ironstones from Greenland, dated at 3.8×10^3 Ma. Like the sediments of later Precambrian times (Section 9.1), these appear to have been *biochemically* precipitated, indicating that life probably arose on Earth not long after the crust had begun to form, and many millions of years before there is fossil evidence in the rocks.

The stromatolites mentioned in Section 9.2 (Figure 34) are the remains of blue-green bacteria and consist of layers of carbonate material either secreted by, or trapped by, the bacteria. Stromatolites occur in rocks as old as 3×10^3 Ma, but are still forming today; for example, in Shark Bay, Western Australia, where the waters are too saline to permit the development of animals such as snails which feed on algae. We cannot be sure exactly when the *first eukaryotic* cells appeared, but they occur in the Bitter Springs formation of Australia, which is about 10^3 Ma old. Some micro-organisms have been reported from Australian rocks around 1.6×10^3 Ma old, and although the cell nuclei that would identify them as eukaryotes have not been found, other cell characteristics suggest that these might also be eukaryotes.

The 1% oxygen level (as a proportion of its present level) that seems to be necessary for respiratory cell development, which was probably achieved before 1.6×10^3 Ma ago, had other important implications for the development of early life. Obviously, this oxygen level offered more protection from u.v. radiation than formerly, and the harmful wavelengths now penetrated to only about 30 cm depth in water rather than the 10 m depth when no atmospheric oxygen was present. Consequently, a number of new, wide-ranging shallow-water environments became available for eukaryotic life in marginal seas and isolated pools.

The oldest Metazoan animal life is believed to date from around 700 Ma ago, and was first described as the **Ediacaran fauna** from sandstones at Ediacara, South Australia (Figure 39). Among the varied forms, some of which have no modern analogues, are primitive jellyfish, sea-urchins, starfish and flatworms. Similar fossils have also been found in late Precambrian rocks of the Charnwood Forest in Leicestershire, and in various other rock formations, from other continents. However, as all the fossils are *soft-bodied impressions* rather than actual hard parts, their detailed identification is disputed in some cases.

FIGURE 39 Reconstruction of late Precambrian life based on the Ediacara sandstone sequence, South Australia. Fossil arthropods (a), sea pens (b), jellyfish (c), worms (d), sea-urchin ancestors (e) and fossils of extinct groups (f), are all represented in this reconstruction. A conspicuous feature of the Ediacaran fauna is the absence of skeletons or shells.

ITQ 21 There were many life-forms in the Precambrian. Why do you think that the Precambrian *fossil* animal record is so sparse compared with that of the Cambrian and later Periods?

The detailed study of fossils (palaeontology) lies beyond the scope of this Course. With the help of the set in your Kit we can try to illustrate a few of the fossil types of the last 600 Ma, so that you can appreciate some of the principles used by palaeontologists, and learn to recognize some of the fossils that are characteristic of at least the last three major stages of Earth history, the Palaeozoic, Mesozoic, and Cainozoic Eras. This is done in the AV sequence at the end of Section 10, 'Fossils as a historical record of life'.

Look first at Figure 40, which shows schematically the various environments in which life is found today. The TV programme 'From Snowdon to the sea' showed how the sediment accumulating today was primarily dependent on the energy of the environment in which it was deposited. Thus, in the still waters of lakes and the quiet parts of the sea, such as estuaries or ocean deeps, fine-grained muds are laid down. In the high-energy regimes of mountain streams or storm-tossed beaches only the coarsest gravels and sands can be deposited. It is therefore obvious that the energy of the environment has an important influence on the types of life that can flourish there, and even more on the chances of organic remains being preserved as fossils. In general, the lower the energy of the environment, the better are the chances of dead organisms being preserved as fossils since they are less likely to be broken up by waves and currents.

In the sea, there are two other parameters that are also important to bear in mind when considering fossil remains: the supply of oxygen and light. Most animals need both oxygen to respire, and some form of food which comes ultimately from photosynthesis. So we can expect that life will be most abundant where oxygen and light are plentiful, that is in the top 30 m or so of the world's oceans. For organisms that must live on the bottom, this means the shallow seas, usually near to the coastline (Figure 40).

Applying the principle of uniformitarianism (Section 3.4) we can expect that the same broad range of environments that we see today have been present in the past, at least since the level of atmospheric oxygen approached present levels.

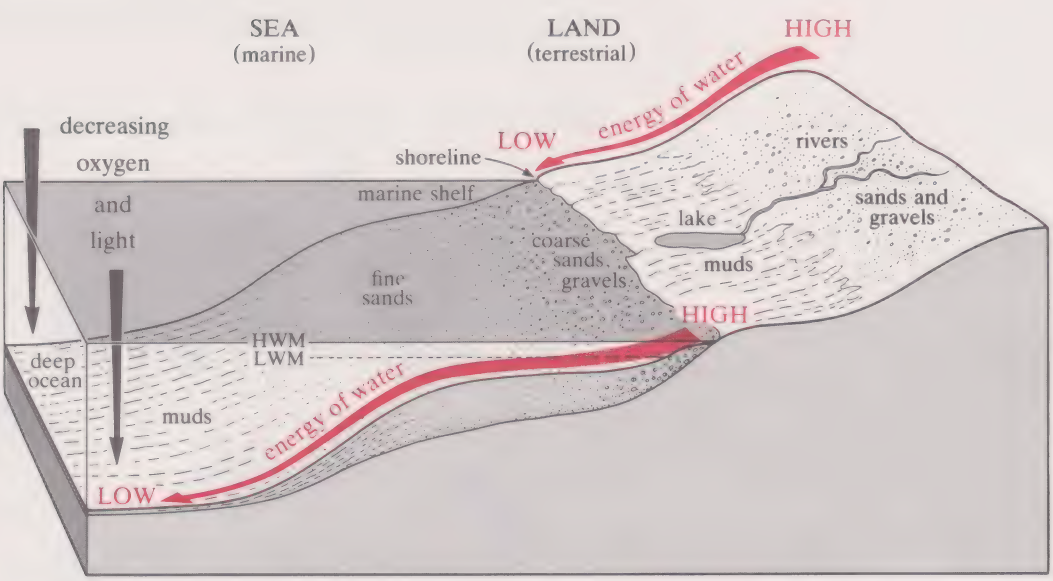


FIGURE 40 Schematic sketch of environments for living organisms. Some indication of the energy of the environment and the penetration of oxygen and light through the surface waters of the ocean is given by the arrows. HWM and LWM indicate high and low water mark respectively.

10.4 LIFE IN THE PALAEOZOIC

About 600 Ma ago, at the end of the Precambrian Era, animals that left hard skeletal remains to form fossils became abundant; this marks the base of the Palaeozoic ('old life') Era. It has been estimated that during the Cambrian Era, between 590 and 505 Ma ago at least 1 200 new marine animal species evolved, and this may be only a small fraction of the total.

ITQ 22 This evolutionary explosion must have had a cause, and also had enormous consequences for the development of life.

(a) Can you suggest a possible relationship between this development of life and the composition of the Earth's atmosphere?

(b) What would be the consequences of this atmospheric change for the habitats available for living organisms to colonize?

Many of the fossil groups found in the Palaeozoic such as the trilobites can be seen to be related to their probable ancestors in the late Precambrian (for example, compare fossil T with (a) in Figure 39). Others, such as the brachiopods (similar to fossil L) and the gastropods (similar to fossil G) are found for the first time in the Cambrian. The last two groups had developed the ability to form a hard external skeleton of calcite. This ability is most striking in the corals (fossil C) which were able to form the first large reefs, an important development, since a reef can provide a sheltered habitat on its landward side protected from the storms of the open sea.

Towards the latter part of the Palaeozoic Era comes one of the most important steps of all, for by this time the atmospheric oxygen level had reached about 10% of its present level, which shielded the harmful u.v. radiation sufficiently to allow organisms to survive on land (Section 9.4).

□ When this oxygen buildup occurred, how would you expect it to be represented in the fossil record?

■ We might expect to find the remains of life which had been able to colonize the land for the first time.

As you will realize if you think about the environments shown in Figure 40, fossils of land-living organisms are much less likely to be preserved than marine ones, because most of the land surface is subjected to erosion rather than deposition of sediment. However, if there are abundant remains of organisms accumulating along the shoreline, then some remains are likely to get swept out to sea, and if there should be a sudden rise in sea-level, considerable 'drowning' of coastal areas will bury any organic remains. This is exactly what we find during the Carboniferous Period (about 300 Ma ago), when the remains of huge tropical forests of primitive land plants accumulated to give much of the present world's supply of coal (hence the name Carboniferous). In fact the earliest land plants are known from their spores from the Silurian Period (440–410 Ma ago), and by the Devonian Period (410–360 Ma ago) there is evidence for quite dense vegetation in places.

ITQ 23 What effects would vegetation cover on the land have on the atmosphere and on the habitats available for animals?

You can see from Figure 6 (Section 2.4) that by the Devonian there were signs that vertebrates had managed to take their first steps onto the land and walking amphibians had evolved. Before the end of the Palaeozoic Era the first reptiles had also appeared. Presumably many of them thrived on the luxuriant vegetation of the 'coal' swamps. It is thought that during the Carboniferous the oxygen content of the atmosphere reached or even exceeded present-day levels. In the coal deposits of Palaeozoic times, huge

amounts of carbon dioxide were taken from the atmosphere and 'locked up' in sediments for 300 Ma. It is this 'fossil' carbon that we are releasing back to the atmosphere today in our coal- and oil-burning power stations. There is still debate about the precise relationship between the present balance of carbon and oxygen between the atmosphere, the oceans and that locked up for millions of years in limestones and coal. With current worries about the possible harmful build up of CO_2 in the atmosphere due to the burning of fossil fuels, this is by no means a purely academic question. It is conceivable that quite small changes in the balance between oxygen production from photosynthesis and carbon dioxide production from respiration or fuel combustion can have large effects on the global climate.

10.5 THE MESOZOIC SEAS

A comparison between the predominant marine fossils found in the Palaeozoic and Mesozoic Eras (Plates 30 and 31) shows that by the Mesozoic some groups have declined in importance, notably brachiopods and crinoids, while the trilobites have become extinct. Other groups have become more important, especially ammonites, bivalves and gastropods, and a variety of land and marine vertebrates, including the dinosaurs (Plate 31), which had diversified into a large number of shapes and sizes.

10.6 LIFE IN THE TERTIARY

You have probably heard at some time of the extinction of the dinosaurs at the end of the Cretaceous Period; the ammonites became extinct too at about the same time, as did many other Mesozoic species. The many theories attempting to account for this 'mass extinction' include disease, gradual changes in climate, a more abrupt climatic change triggered by a series of large volcanic eruptions, and even the suggestion that a comet hit the Earth, causing a huge explosion that changed the climate overnight. In spite of the attraction of such 'catastrophic' explanations, most palaeontologists believe that the extinctions took place quite gradually (over millions of years) and were not all synchronized by an extraterrestrial event. One colourful suggestion is based on the sensitivity of dinosaur eggs to a slight increase in ambient temperature, an increase resulting in the hatching of more male than female eggs. As the number of females declined so reproduction suffered, and one is left with the riveting spectacle of the last female of each species being courted by more males than she could handle. Not likely, you may think, but one of the fascinations of geology is that it's difficult to disprove many of the theories because they deal with events that happened so long ago!

By the beginning of the Cainozoic Era (65 Ma ago) the sea floor and land had taken on a decidedly modern look. On land, flowering plants predominated, largely replacing the more primitive conifers and ferns of the Mesozoic (Plate 31). Similarly, mammals were now occupying most of the herbivorous and carnivorous niches formerly occupied by the reptilian dinosaurs, and the air had now been conquered by the birds, the descendants of the dinosaurs. The greatest proliferation of all came in insects, many of which were associated with flowering plants.

In the seas, bivalves, gastropods and crustaceans (crabs, shrimps, etc.) now occupied niches formerly dominated by brachiopods, ammonites and crinoids. Many of the species found in the rocks of Tertiary age can still be found living today.

This completes our rapid journey through Earth history, and it is now time to return to your Kit fossils to see how they fit into this broad picture.

10.7 FOSSILS AS A HISTORICAL RECORD OF LIFE (AV SEQUENCE)

For this AV sequence (on Tape 4, Side 2, Band 3) you will need the fossil specimens, rock samples S6 sandstone and S7 limestone, and the hand lens from Part 1 of your Kit.

As you listen to the tape, write the appropriate names or fossil letters in the spaces in Figures 41 and 42. You may find it useful to refer to Figure 40 and Plates 30 and 31.

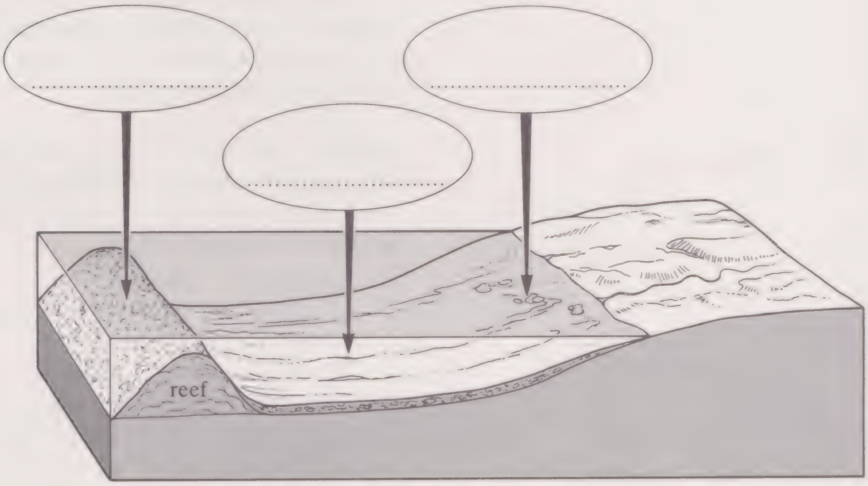


FIGURE 41 Reconstruction of the Silurian sea floor (cf. Plate 30), for use with the AV sequence, Section 10.7.

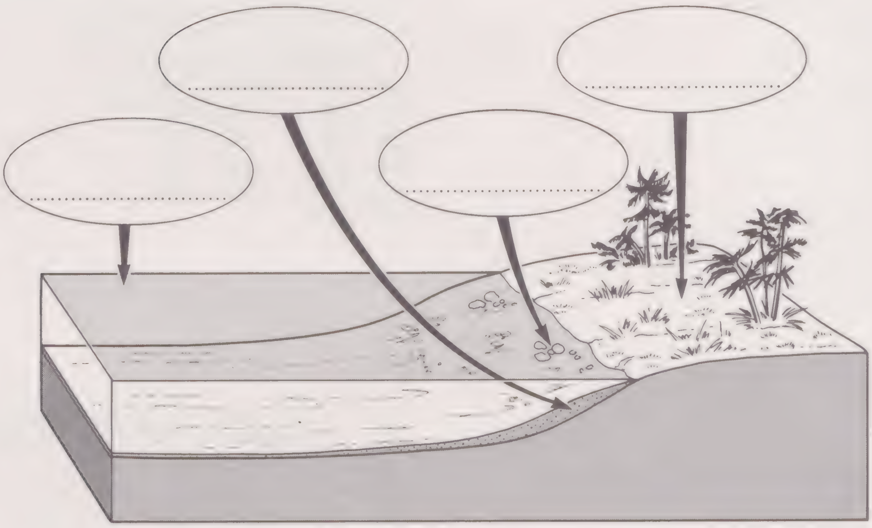


FIGURE 42 Reconstruction of Jurassic sea floor (cf. Plate 31), for use with the AV sequence, Section 10.7.

SUMMARY OF SECTION 10

1 Very early in the Earth's history, amino acids and nucleic acids were probably synthesized and then concentrated in the atmosphere and hydrosphere system by processes such as those of Miller's experiments described in Units 17–18, Section 8.1.

2 The earliest life developed from these compounds as prokaryotes (bacteria) well before 3 000 Ma ago. These were anaerobic, disposing of their oxygen biochemically to iron compounds, leading to the formation of banded iron ore formations in the oceans.

3 More efficient aerobic bacteria probably evolved when atmospheric oxygen reached about 1% of its present level.

4 As atmospheric oxygen increased, a more effective ozone layer developed, which protected first shallow-water environments and then the land

ECLIPTIC PLANE

from harmful levels of u.v. radiation and so allowed life to spread. Thus the first eukaryotes are found at 1 000 Ma ago, metazoans in shallow water at 700 Ma ago, abundant shelly organisms at about 600 Ma ago and the first land plants at about 440 Ma ago.

5 During the Palaeozoic Era, small shelly organisms, such as trilobites, crinoids and brachiopods, were predominant in the seas, and primitive fern-like plants and amphibians were the first to colonize the land.

6 The Mesozoic Era was dominated by ammonites, echinoids and reptiles in the sea, while on land the dinosaurs proliferated.

7 Early Tertiary times brought an abrupt change and the development of 'modern' fauna, with bivalves and gastropods most abundant in the sea, and mammals, birds and insects dominating the land, which was now covered in flowering plants.

SAQ 19 To show that you have understood the interrelationships between atmosphere, evolution and the geological record, allocate the various key events (A–J) in the following list to appropriate points in the geological time-scale (i–ix).

A Appearance of mammals
B First soft-bodied Metazoa; the Ediacaran fauna
C Earliest definite eukaryotes
D Oldest known stromatolites
E 1% of the present atmospheric oxygen level established
F Origin of the first banded chert–haematite sequences (BIFs)
G Earliest indirect evidence of Precambrian life
H First major period of coal formation
I Inferred appearance of land plants
J Establishment of redbeds

Time/Ma before present	
(i) 250	(vi) 1600–2 200
(ii) 300	(vii) 3 000
(iii) 440	(viii) 3 400
(iv) 700	(ix) 3 800
(v) 1 000	

11 CLIMATIC CHANGE AND ICE AGES

11.1 CLIMATIC BELTS

So far, we have been concerned with both the origin and evolution of the Earth, its oceans, atmosphere and living organisms throughout geological time. Now we focus attention on the nature and controls of climatic change at the Earth's surface. This is best achieved by reference to the abundant evidence from the most recent parts of geological history.

Although there have been changes in gas concentrations in the atmosphere during Earth history, which must have caused its temperature to vary, many of the factors affecting climate have probably changed very little. The well-defined climatic belts (Figure 43) which characterize the modern Earth have migrated relative to the Poles and Equator but are thought to have borne a clear relationship to latitude throughout geological time.

This is because geophysical evidence suggests that the Earth's rotational axis has kept a fairly constant angle to the **ecliptic plane** (the plane of the Earth's orbit around the Sun). Small cyclic changes in this angle do occur, but any major departure from this position would have had catastrophic effects on climate. Figure 44 shows that the radiant energy from the Sun

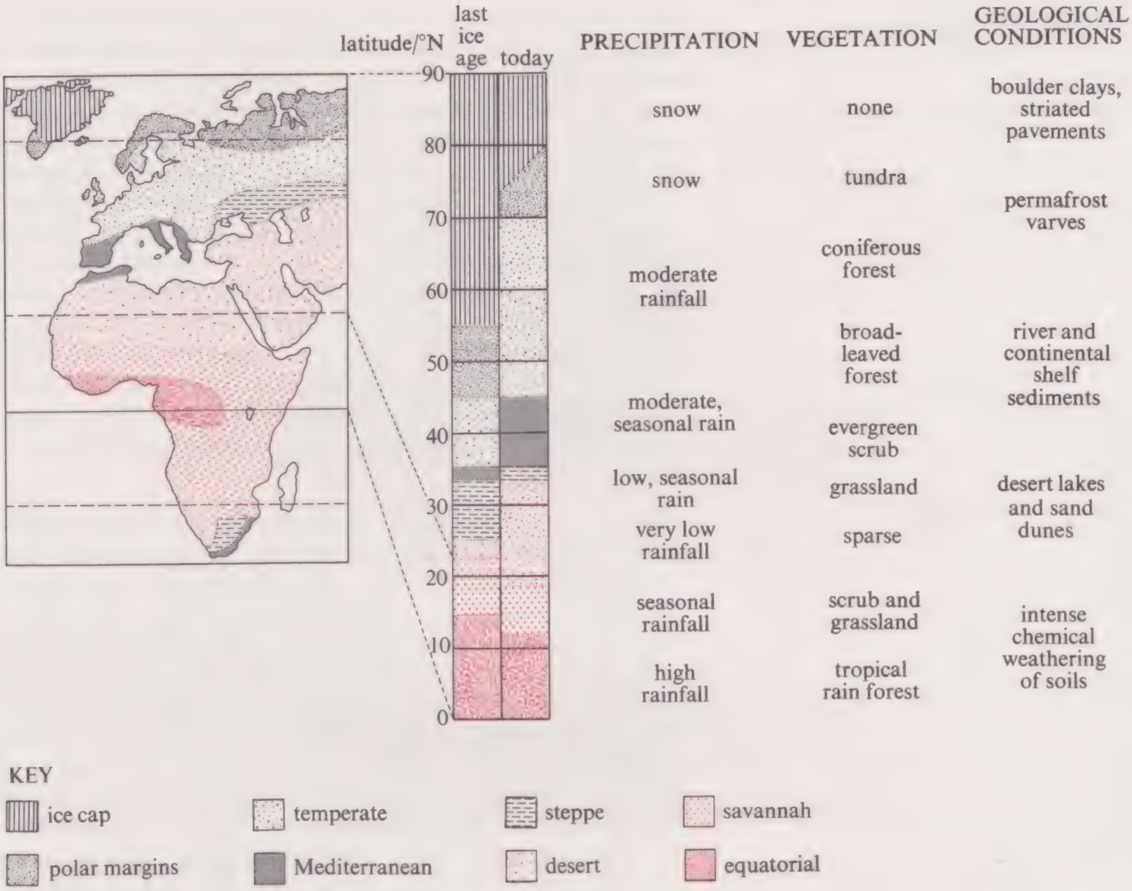


FIGURE 43 Present-day latitudinal distribution of the Earth's climatic and vegetational belts. The two vertical columns express the relative latitudinal extent of different climatic belts during the last glaciation and today. Geological conditions and the deposition of various rock types are also a function of climatic environment: the geological conditions indicated can therefore be used to diagnose ancient environments.

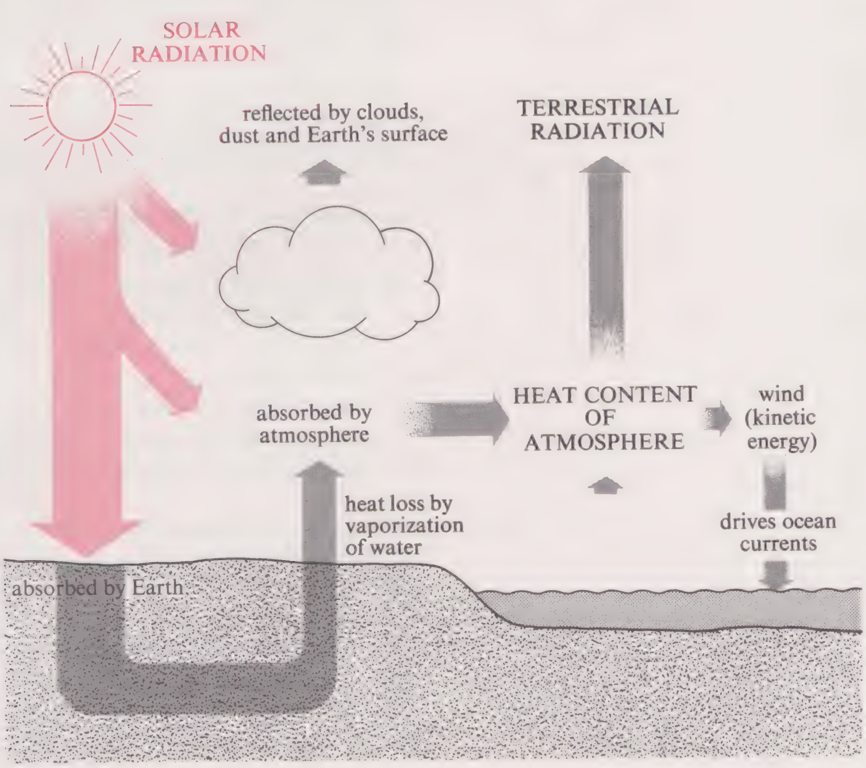


FIGURE 44 Energy flow in the atmosphere.

GREENHOUSE EFFECT

ICE AGE

provides the energy to drive the atmospheric circulatory system. Incident energy is absorbed and re-radiated by the atmosphere and the Earth's surface. Early in Earth history, the higher CO_2 content of the atmosphere may have inhibited re-radiation by the Earth, and surface conditions may have been much warmer when early life-forms were evolving. The reason for this is as follows. Carbon dioxide is an efficient absorber of the relatively long-wavelength terrestrial radiation (in the infrared region of the electromagnetic spectrum), but transmits shorter-wavelength radiation. Hence, the Earth's atmosphere transmits most of the incident solar radiation, which is of short wavelength, and this transmission is largely unaffected by the concentration of CO_2 in the atmosphere. However, absorption of the long-wavelength terrestrial radiation increases as the CO_2 concentration increases, and consequently the re-radiation of heat from the air to the ground increases as well. Because of the similarity of absorption characteristics between CO_2 and glass, the phenomenon is known as the **greenhouse effect**.

There is good geological evidence that latitudinal migration of climatic belts has occurred in the last 10^3 Ma. Today, ice-sheets are largely restricted to the polar regions, but only 20 000 years ago they extended much further—into Eurasia and North America, for example. In Units 7–8 you met evidence of glaciation of the Southern Hemisphere about 300 Ma ago. If we look at the geological record as a whole, episodes of repeated glaciation (or **ice ages**) have occurred at periodic intervals. In addition to the recent Quaternary and the Permo–Carboniferous Ice Ages, there is certain evidence for glacial activity in the Ordovician and at several scattered periods within the Precambrian. In contrast to these periods, for the whole of the Mesozoic (spanning some 185 Ma), no evidence for glaciation, even polar ice-caps, has been recorded, and quite temperate climatic conditions are believed to have reigned even at polar latitudes. By studying these long-term and more recent changes in climate, certain clues as to the cause of ice ages can be found.

11.2 RECENT CLIMATIC CHANGES

Because we live in a geological Period of unusually active climatic change (the Quaternary, which represents the last 2 Ma), it is instructive to examine the recent scale of these changes. Although this period is geologically short, it has had an enormous influence on those landscapes that were subject to glacial erosion and deposition, as you have seen in Unit 27 and its associated TV programme. Similarly, it has affected the vegetation and fauna because climatic shifts enforced huge migrations and changes of habitat.

□ How might plant and animal species have been affected by these environmental pressures?

■ Those species that were unable to migrate to warmer areas or adapt to the colder conditions in their own areas became extinct. Many species, such as the Woolly Mammoth and the Great Irish Elk, did become extinct during the Quaternary Ice Age, whereas others developed new adaptations; that is, *their rate of evolution increased*. It is frequently argued that the rapid development of *Homo sapiens* was a response to this challenge of changing environments.

For much of the last million years, average annual temperatures over land surfaces have been lower than those of today by as much as 10 °C. The ice-sheets which repeatedly covered much of North America and Eurasia last retreated from Britain about 10^4 years ago. In the more immediate past, you may well remember the weather of exceptional seasons such as the hot, dry summer of 1976 or the severe winters of 1947, 1963 and 1986. Whenever such seasons occur, there is a bout of speculation that fundamental changes in our weather patterns, such as the return of a glacial period,

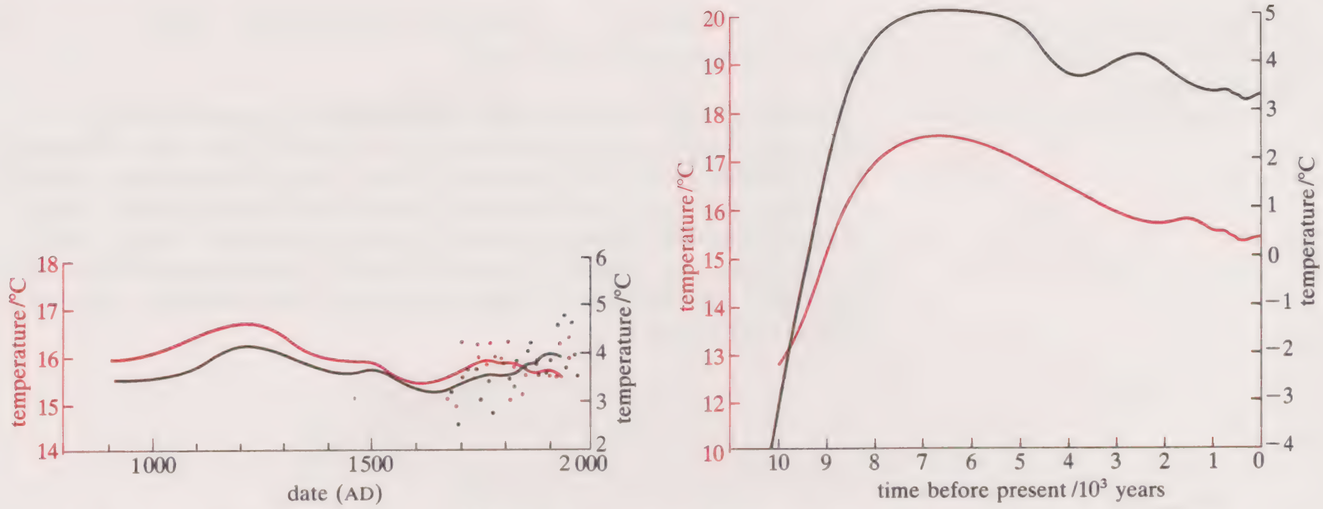


FIGURE 45 (a) Average air temperatures for lowland central England: (i) high summer (July–August), shown in red; (ii) winter (December–February), shown in black. Continuous lines represent 100-year averages, dots the averages for each decade since instrumental records have been kept.

(b) Estimated average (i) summer (red) and (ii) winter (black) temperatures (± 1 °C) for southern England over the past 10×10^3 years.

are taking place. These occurrences can really only be judged in the light of statistical analysis of data over much longer periods.

Figures 45a and 45b show reconstructions of temperatures in England for the last 1 100 and 10 000 years, respectively. Figure 45a is based on continuous instrumental records for the last 300 years and inferred from written historical records for earlier times. Figure 45b is derived largely from climatic interpretation of the evidence of fossil plant and animal remains found in bog peats and lake sediments laid down since the disappearance of the last ice-sheets in northern Europe about 10 000 years ago.

ITQ 24 Can you suggest by what method the absolute time-scale applied to Figure 45b was obtained?

ITQ 25 From the curves in Figure 45, calculate the total range of average winter and summer temperatures (a) over the past 100 years; (b) over the past 900 years (Figure 45a); (c) over the past 7 000 years (Figure 45b).

From these data you can see that climatic fluctuations have been taking place on a variety of scales. Those we know most about statistically are in terms of centuries, though we know virtually nothing about their causes. For example, in the early Middle Ages it was warm enough for Viking settlements to survive in Greenland and for vineyards to be developed quite widely in Britain. By 1 400, summer pack ice between Greenland and Iceland meant that contact by sea with Greenland was lost, and the settlements were abandoned. Likewise, vineyards ceased to be an economic proposition in Britain, since the fruit often failed to ripen. During the 'Little Ice Age', between the 17th and 19th centuries, winters tended to be long and cold, giving rise to the Christmas card images of stage coaches in deep snow and skating on the frozen Thames. From about 1860 onwards there was a general rise in both winter and summer temperatures and also a world-wide retreat of glaciers in mountain areas; but since 1950 statistical analysis suggests that the climatic pendulum may be beginning to swing back towards cooler conditions once more. But these short-term fluctuations are, in turn, superimposed on larger changes measured in many thousands of years (see Figure 45b), which are the subject of the next Section.

INTERGLACIAL DEPOSIT

POLAR FRONT

11.3 CLIMATIC CHANGES DURING THE QUATERNARY ICE AGE

From Figure 45b you can see that last glacial period ended about 10×10^3 years ago. But the geological evidence from repeated thick layers of poorly sorted boulder clay (or till) sediments (Figure 46) and ice-scratched surfaces suggests that several glacial advances characterized the Quaternary Ice Age. Indeed **interglacial deposits** of sand and clay, containing fossils of warm-loving plants and animals, intervene between successive glacial tills, and apparently cold and warm climatic conditions have alternated on a 10^4–10^5-year time-scale.

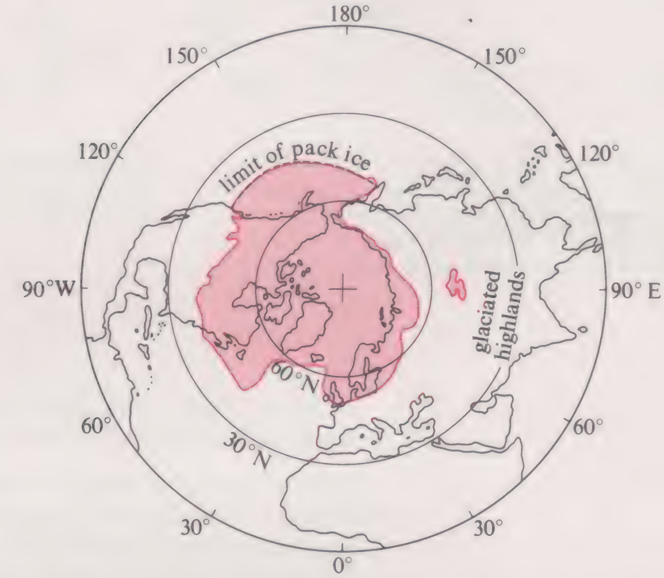


FIGURE 46 Northern Hemisphere geography at the time of the last climax of glaciation about 18×10^3 years ago. The shaded area contains oceanic pack ice and glaciated land-masses. All formerly glaciated areas now contain deposits of boulder clay (till). Although Siberia and parts of Alaska were, and indeed still are, subject to a very cold climate, snowfall is relatively low. Consequently, it barely balances out the effects of summer melting, and so major ice-sheets are not developed in these areas.

ITQ 26 Think again about the dating methods that have been applied to recent lake deposits (ITQ 24). Could these be used on interglacial lake deposits to obtain the age and duration of interglacial periods?

When a glacier or ice-sheet advances, its rock-load usually erodes and destroys the recent sediments of lakes and bogs that lie in its path—and also the boulder clays of older glaciations. Thus, it is difficult to build up a detailed stratigraphic succession. Even if interglacial deposits survive, they cannot be dated by an isotopic method, so how can we build up an accurate picture of climatic change during this important period?

Generally the continents are areas of erosion, and the oceans areas of deposition. Sediment cores obtained during the Deep Sea Drilling Project (Units 7–8, Section 4.8) have provided a fairly continuous depositional record for the whole Quaternary Period.

Studies of fossils, and the chemistry of water and sediments, have all revealed evidence of the same climatic fluctuations that brought glaciation to the continents. Furthermore, the sediments of the ocean floor can be dated and correlated over wide areas. The geological record from deep-ocean cores suggests that within the last 1.8 Ma there may have been no fewer than *seventeen* major glacial–interglacial cycles, with the last three major glacial stages having been particularly severe. A major climatic indicator is the position of the polar weather front in the north-east Atlantic.

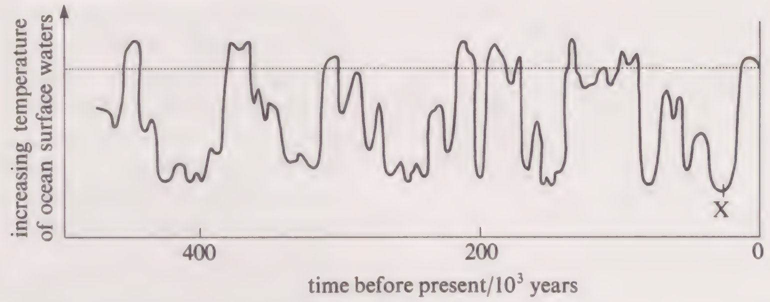


FIGURE 47 Fluctuations in the relative temperature of ocean surface waters over the past 400×10^3 years in the north-east Atlantic. For example, the point X corresponds to the maximum advance of glaciers during the last glacial period 18×10^3 years ago (see Figure 45b for the last 10×10^3 years). Data are based on the ratios of cold-loving to warm-loving organisms in deep-sea cores. The horizontal line represents estimated average present-day temperature.

The **polar front** is the limit of very cold polar air where it meets warm air from lower latitudes. The polar air strongly influences the nature of the plankton because these microscopic organisms float in the top 100 m of ocean waters. Some of these organisms have minute shells made of calcium carbonate, which become incorporated in the sediment on the ocean floor. In the deep-sea cores, changes in the types of fossil fauna can be used to estimate quite precisely the changes in temperature of the surface waters in which these animals lived. Figure 47, which shows these relative temperature variations, is based on the *ratios* of cold-loving to warm-loving organisms extracted from deep-sea sediments in the north-east Atlantic and to the south of the present polar front.

If you compare the absolute temperature for the last 10×10^3 years given in Figure 45 with the relative temperature scale of Figure 47 (the point X is 18×10^3 years ago), you will note that, on a 400×10^3-year time-scale, average summer and winter temperature fluctuations must be about 10 °C and 15 °C, respectively. Bearing in mind the answers to ITQ 25, it is evident that the range of average temperature increases as the time-interval considered increases. This is not surprising in view of the glaciations recorded in Figure 47.

ITQ 27 Examine Figure 47 and estimate what percentage of the last 400×10^3 years had a climate as warm as or warmer than it is today.

To a first approximation, notice that the major glacial–interglacial periods seem to fit a 100×10^3-year cycle, but in fact the pattern is not as regular as that. Interglacial intervals are of varying lengths, sometimes 30×10^3 years or less. The present interglacial period had lasted approximately 10×10^3 years from the melting of the previous ice-sheet (see Figure 45), through a period warmer than today, to the re-establishment of very cold bleak conditions. You should now be able to consider how long the present interglacial period has lasted so far in comparison with previous ones.

11.4 GLACIATION AND SEA-LEVEL CHANGES

What effect would you expect the development of large ice-sheets to have on sea-level? There are two factors involved, one of which has already been discussed in Units 7–8.

First, as glaciers and ice-sheets build up, very large amounts of water are taken from the oceans and stored on the continents as ice. Water in this form is returned at a much slower rate than rainfall. Consequently, during each of the major periods of glaciation, world sea-levels fell by as much as 120 m, with a return to higher levels during the intervening interglacial stages. Such fluctuations, caused by the melting and accumulation of ice,

EUSTATIC CHANGES

SUNSPOT CYCLES

are called **eustatic changes** in sea-level. On steep rugged coastlines with deep water offshore, there would be little change in the position of the coastline, but there are broad continental shelves, such as those around the north Atlantic (see the World Ocean Floor map), the extension of land-masses would be considerable during periods of sea-level fall due to glaciation. So the British Isles, for example, became part of the European continental land-mass and a land bridge became established between the Old and New Worlds via the Bering Strait.

The second factor affecting land/sea is isostatic adjustment (Units 7–8, Section 4.4). Ice-sheets weigh a great deal and so downwarping (or sinking) of the crust occurs beneath them. Figure 48 shows how Scandinavia was depressed nearly 800 m during the last glaciation by an ice-mass over 2 000 m thick. As the ice melts at the end of a glaciation, eustatic changes occur rapidly and sea-level rises in a short period of time. However, isostatic recovery, though rapid at first, continues at a slow rate for a very long time. Today, 10 000 years after the final melting of the Scandinavian ice, the land-mass in central Scandinavia is still rising at a rate of nearly 1 cm per year, leaving raised beaches such as those which also occur in northern Scotland. Other characteristic landforms associated with glaciations are the frost-shattered peaks and U-shaped erosional valleys shown in the TV programme 'From Snowdon to the sea'.

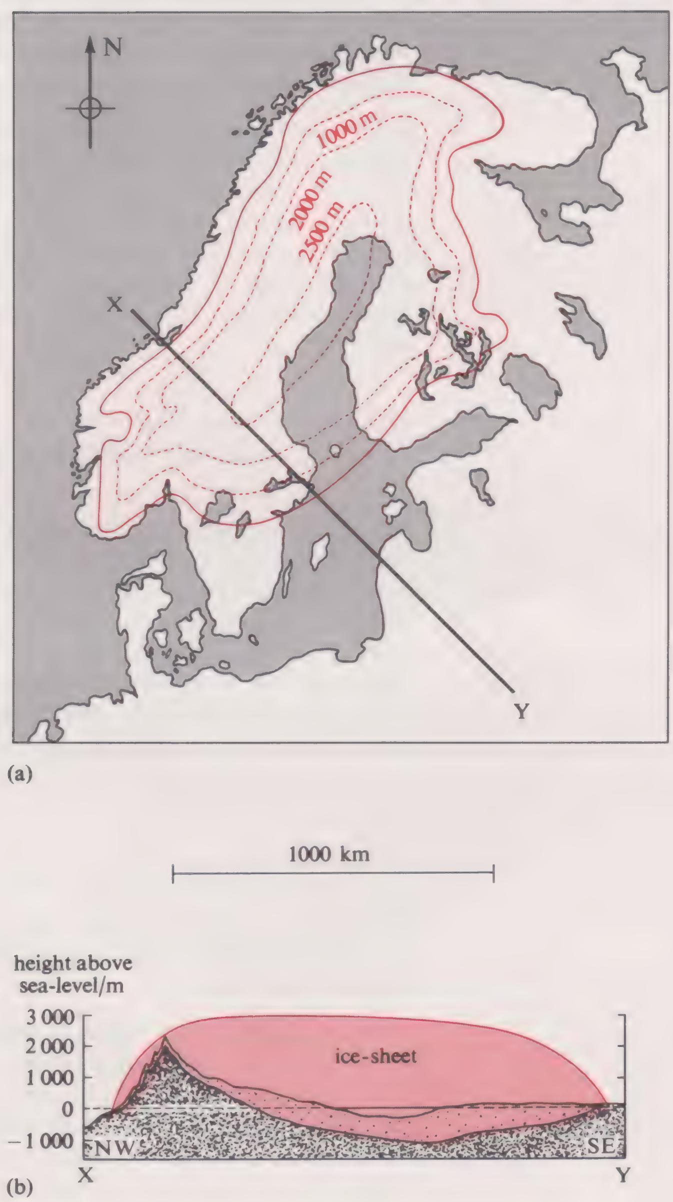


FIGURE 48 (a) Estimated surface contours of the Scandinavian ice-sheet, and (b) estimated cross-section of the ice-sheet during the maximum glacial advance of the last ice age. The solid line indicates the maximum extent of the ice-sheet. The heights given are related to present-day sea-level. In (b) the dense stipple indicates the height of bedrock during glacial downwarping and the light stipple refers to its height after post-glacial isostatic recovery.

ITQ 28 During ice ages, which areas of the world are likely to be affected most (a) by eustatic, and (b) by isostatic changes in land/sea-level? Will these changes reinforce each other or tend to cancel each other out?

11.5 THE CAUSES OF ICE AGES

Many theories, mostly speculative, have been put forward to explain the occurrence of ice ages. Frankly, the causes of extensive glaciation are not yet understood. However, this phenomenon appears to be the most powerful manifestation of a very complex pattern of climatic variability. The two major questions which must be answered, but whose solutions are not necessarily related, are:

(a) Why should ice ages only occur at particular times during geological history?

(b) What factors control the complex and irregular pattern, both in time and in intensity, of climatic changes during the present period of the Quaternary Ice Age?

One group of theories is largely concerned with variations in solar radiation reaching the Earth, that is, with *extraterrestrial factors*. Other theories relate to changes in various *elements of the Earth's climatic system*, such as the deep circulation of the ocean, the CO_2 balance between living organisms, the atmosphere and the hydrosphere (Section 9.4), or the long-term growth and decay rhythm of ice-sheets themselves, as being the critical factors. Yet another possibility is that continental drift itself may be highly significant, especially with regard to question (a) above.

□ In what way might the distribution of continents and mountains affect world climatic conditions?

■ The position of the continents naturally affects ocean currents, which are very important climatically. For example, the development of the circum-Antarctic current in mid-Tertiary times may have been responsible for the present-day Antarctic ice-cap. Also important are the locations of high mountain ranges, which provide a source from which ice can spread out into lowlands well below the regional snow level.

Factors operating from outside the Earth will now be considered. As you know from Section 11.1 (Figure 44), the temperature of the Earth's surface is overwhelmingly dependent on solar energy. Cycles of solar activity—**sunspot cycles**, characterized by the occurrence of dark patches on the Sun's surface—have been observed to have periods of 11 and 22 years (Figure 49). Sunspot minima are known to correlate with a polarwards displacement of climatic belts, leaving the middle latitudes generally warmer and drier than when the Sun is quiet. The significance of sunspot cycles in causing major shifts of climate reflected in glacial periods is a matter of some controversy. Recent studies of sediments from Australia 680 Ma in age demonstrate cycles of 11 and 22 years, which implies that sunspot activity may have had a remarkably constant period through much of geological time. Further-

FIGURE 49 The sunspot cycle consists of variations in the sizes, numbers and positions of sunspots, expressed quantitatively in terms of the 'sunspot number' (vertical axis). The number of sunspots reaches a maximum soon after the beginning of each cycle and decays to a minimum in 11 years. The magnetic polarity of the sunspot groups reverses in each successive cycle, so a complete cycle lasts 22 years.

more, the preliminary results from 2 500 Ma old banded ironstones suggest a similar period. Even if variation in output of solar energy is not responsible for climatic shifts on the Earth, receipt of solar radiation may have been affected by the passage of the Earth's orbit through areas of interstellar dust. This remains one more untested hypothesis.

Next, there are the effects of *geometric variations in the Earth's orbit* around the Sun. These variations occur on a 96×10^3-year cycle. Also, there are small variations in the tilt of the Earth's axis of rotation with respect to the ecliptic plane, which have a period of about 40×10^3 years. Finally, the Earth does not simply rotate about its own axis and orbit the Sun, but its axis traces out a cone like a top, with a period of 26×10^3 years. The cumulative effect of all these movements was calculated by the Yugoslavian geophysicist, M. Milankovitch. According to his calculations, changes of solar radiation reaching the Earth should cause seasonal fluctuations of 2–3 °C at some latitudes. The strength of the Milankovitch hypothesis is that when the sum of the three periods is calculated, there is a statistical correlation with the time-scale of glacial changes recorded in deep-sea cores (Figure 47). So orbital fluctuations may act as a pacemaker for glaciations, but they do not explain why ice ages occur, for the Earth's orbital properties were probably no different in the Mesozoic when no ice ages occurred.

However, the Earth's radiation budget and climate can equally well be affected by changes within the atmosphere itself (see Figure 44), and the oceanic and atmospheric circulations can be affected by the disposition of the continents. Another important property is the 'reflectiveness' of the Earth, which is called the albedo. This is a measure of how much radiation received by the Earth is reflected back into space. Cloud cover (a function of atmospheric H_2O content and temperature) has the effect of increasing the Earth's albedo, and thereby increasing the amount of energy (received by the Earth) that is directly reflected. You will recall from Section 11.1 that the amount of CO_2 in the atmosphere is also a heat-regulating device, for an increase in CO_2 decreases radiation losses and warms the atmosphere: the greenhouse effect. As you know from Section 9.4, there is a relationship between forest cover and CO_2, although this is quite complicated because living forests absorb much CO_2 in photosynthesis, and are themselves a considerable reservoir of carbon, much of which is released as the forests decay. This has implications for the CO_2 budget of the hydrosphere–atmosphere system, since, together with limestone formation, this process has reduced the 'free' CO_2 content of the system throughout post-Cambrian times. The implications of the release of vast quantities of this CO_2 by the burning of fossil fuels may well include an increase of surface temperatures and a melting of polar ice. In turn, this may lower the Earth's albedo, in that reflective polar ice-caps would shrink in area, thus emphasizing the long-term effects of CO_2 release.

ITQ 29 When ice-sheets begin to form or expand at the onset of a major glaciation, what effect will this have on the albedo of the Earth and on the persistence of the ice-sheets?

It is also known that volcanic eruptions, such as that of Krakotoa in 1883, which put a lot of dust into the atmosphere, tend to produce a striking global decrease of incident solar radiation. Such decreases are temporary, but many of the coldest and wettest summers in Britain have occurred following times of high volcanic dust input into the stratosphere and upper atmosphere. Atmospheric dust is unlikely to be a major cause of climatic change, but could be important in reinforcing or opposing the effects of other factors.

In conclusion, the answers to the problem posed at the beginning of this Section are unlikely to be simple. A number of factors determine the Earth's climate, and these factors result in a system that is more complex than we

can currently understand. Small changes in one factor, for example ocean current or wind circulation, may have quite unexpected effects. It seems that continental drift and the disposition of the continents may well provide the best correlation with the occurrence of ice ages, and that orbital motions influence climatic variations, affecting the extent of glaciation within the ice ages. If this is so, the forecast for the next 20×10^3 years is towards extensive Northern Hemisphere glaciation and cooler climate, that is, disregarding the influence of human activities.

SUMMARY OF SECTION 11

1 Ice ages, comprising repeated periods of glaciation, are recognized from the associated boulder clay (or till) deposits at various times in the Earth's history.

2 Detailed studies of marine sediments deposited during the recent (Quaternary) Ice Age show that average annual temperature oscillations of 10–15 °C have occurred on a 10^4–10^5-year time-scale.

3 The pattern of land and sea-level changes during a glacial period is complex, reflecting (a) rapid eustatic sea-level changes due to freezing and thawing of ice-caps, together with (b) the relatively slow isostatic response of glaciated land-masses.

4 The most likely causes of glaciations and ice ages in general are:

(a) geometric variations in the Earth's orbital and axial rotations and periods;

(b) the disposition of the continents, which affects the pattern of ocean water and atmospheric gas circulation.

5 The release of CO_2 by human activities, particularly during the last century, may be causing a long-term change in the pattern of climatic response to the factors identified in point 4.

SAQ 20 Which of the following statements are correct?

A Most ice ages recorded in the stratigraphical record comprised several glaciations separated by warmer periods, when interglacial deposits were laid down.

B Eustatic changes of sea-level occur following a glaciation as the land surface rises.

C The polar front is the furthest limit of cold polar air from the poles, and this reaches its most northerly point in the Northern Hemisphere during an interglacial period.

D Solar energy output is known to vary with periodicities of 11 and 22 years; these correlate with the fluctuation of sunspots on the Sun's surface.

E The Earth's albedo increases when large areas are covered by ice and snow, which reflect sunlight.

SAQ 21 Figures 50a and 50b represent the relationship between modern sea-level and former shoreline (sea) levels over the past 15×10^3 years in two different areas of Europe. How do you account, in terms of eustatic and isostatic changes, for the difference in the two curves and the patterns of change which they show?

Don't be too concerned about the hump in Figure 50b; it will be explained in the SAQ answer.

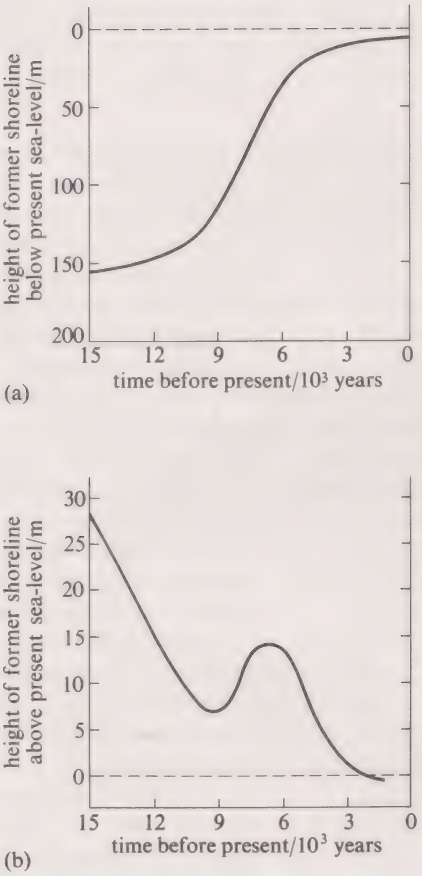


FIGURE 50 Variation of sea-level over the past 15×10^3 years in two areas of Europe.

REMOTE SENSING

12 FRONTIERS OF GEOLOGY (TV PROGRAMME)

You have now come to the end of seven Earth science Units, finishing in this double Unit with a review of major events of Earth history. Presenting such a grand subject in so short a space may give you a misleading impression that all the major problems of Earth sciences have now been solved. Why do we still do research in Earth sciences? Well, in this programme we are taking a look at some of the unsolved questions that Earth scientists are still facing, and the tools they are using to tackle them.

We begin the TV programme with the study of meteorites. The great majority of meteorites have ages of 4 500–4 600 Ma, the age of the Solar System. However a small group of eight individual achondrites, known as SNC meteorites after the locations of the first three to be identified, give much younger ages, some giving an age of 1 300 Ma, another a possible age of 180 Ma. These fragments could therefore come from a large, geologically active, planet where magmas were still being generated long after the formation of the Solar System. Since the late 1980s it has been suggested that these meteorites come from Mars. The composition of the Martian atmosphere is known from the 1975–6 American Viking missions, which landed two probes on Mars. One of the characteristic features of a Martian atmosphere is a much higher ${}^{15}_{7}N/{}^{14}_{7}N$ ratio than is found in terrestrial atmospheric nitrogen. Analysis of trapped nitrogen from a SNC meteorite has shown a substantial enrichment in the heavier nitrogen isotope, and it is now widely accepted that these fragments have a Martian origin. Studies by Dr Colin Pillinger and his group from the Open University on the carbon, oxygen and nitrogen isotopic characteristics of SNC meteorites are providing new information on surface processes on Mars. These findings are essential for our understanding of the geological evolution of the planet, but they also identify problems which can be tackled by the Soviet–British collaboration in plans to launch a spacecraft to one of the Martian moons in the next few years.

On a smaller scale, both in time and distance, the field geologist studies the movement of the tectonic plates of the Earth's lithosphere, and the integration of field techniques with laboratory studies is shown in the next part of the TV programme. From Figure 46 in Units 7–8, it may seem that all the plate boundaries are well established. In fact, virtually every boundary remains the subject of continuing research to resolve its precise geometry, and the number of smaller plates present. One of the least known areas of the continental crust is the Tibetan Plateau; this is particularly tantalizing because it is one of the few undisputed examples of active continent/continent collision. It has been known for some years that the Himalayas result from collision between India, which had broken away from a vast southern land-mass called Gondwana, and the rest of the Asian continent, about 50 Ma ago. The northern boundary of the Indian plate lies just north of the Himalayas. This collision resulted not only in the formation of the Himalayan range, but also in the doubling of the thickness of continental crust underneath the entire Tibetan Plateau. You should remember from Units 7–8, Section 4.4, that isostasy requires that an increase in the thickness of low-density continental crust will result in uplift, which has certainly happened in Tibet and the Himalayas. In order to understand *how* the continental lithosphere has deformed, structural geologists, working with geochemists, palaeontologists, palaeomagnetists and sedimentologists have had to work closely with a relatively new laboratory technique; **remote sensing**, which generates images of the Earth's surface from data gathered by satellite. One of the great advantages of modern remote-sensing techniques is that they are sensitive to radiation from beyond the visible range of the electromagnetic spectrum. This enables geologists to use the wavelengths that are most suitable for detecting features of interest, whether these are the contrast between rock types with different reflectance properties, or the hot areas in volcanic regions which generate intense short-wavelength radiation. Dr David Rothery of the Open University has made a study of the

satellite imagery of the Tibetan Plateau, and these images provide not only a record of the rock types exposed on the surface including unexpected tracts of recent volcanic activity, but also clear traces of rift valleys and major faults which have allowed continental crust to move out sideways in response to continental collision (see Plate 32).

Another example of current research shows that neither high-tech instrumentation nor exotic foreign locations are necessarily required for important advances in geology. In 1983 an amateur geologist, William Walker, came across a huge claw-like object in a Surrey quarry, which he took to the experts in the Natural History Museum in South Kensington. After 4 years of very painstaking extraction from the enclosing rocks, *Baryonyx walkeri*, a large carnivore, described as the most important dinosaur discovery found in Europe this century, was unveiled to the public (Figure 51). 1987 also brought a spectacular display of complete dinosaur skeletons from China at the National Museum of Wales in Cardiff. The detailed study of the modes of life and the causes of extinction of animals such as the dinosaurs remains one of the most fascinating areas of research and speculation in geology. We end by looking at the very delicate work involved in investigating the possible chemical traces of an extraterrestrial event which may have been involved in the extinction of the dinosaurs.

We should like to leave you with the impression that Earth sciences employ an extraordinarily wide range of skills. By combining the principles and techniques of physics, chemistry and life sciences with field techniques that are unique to Earth Sciences, we are gradually unravelling the history of the Earth and the nearby planets.

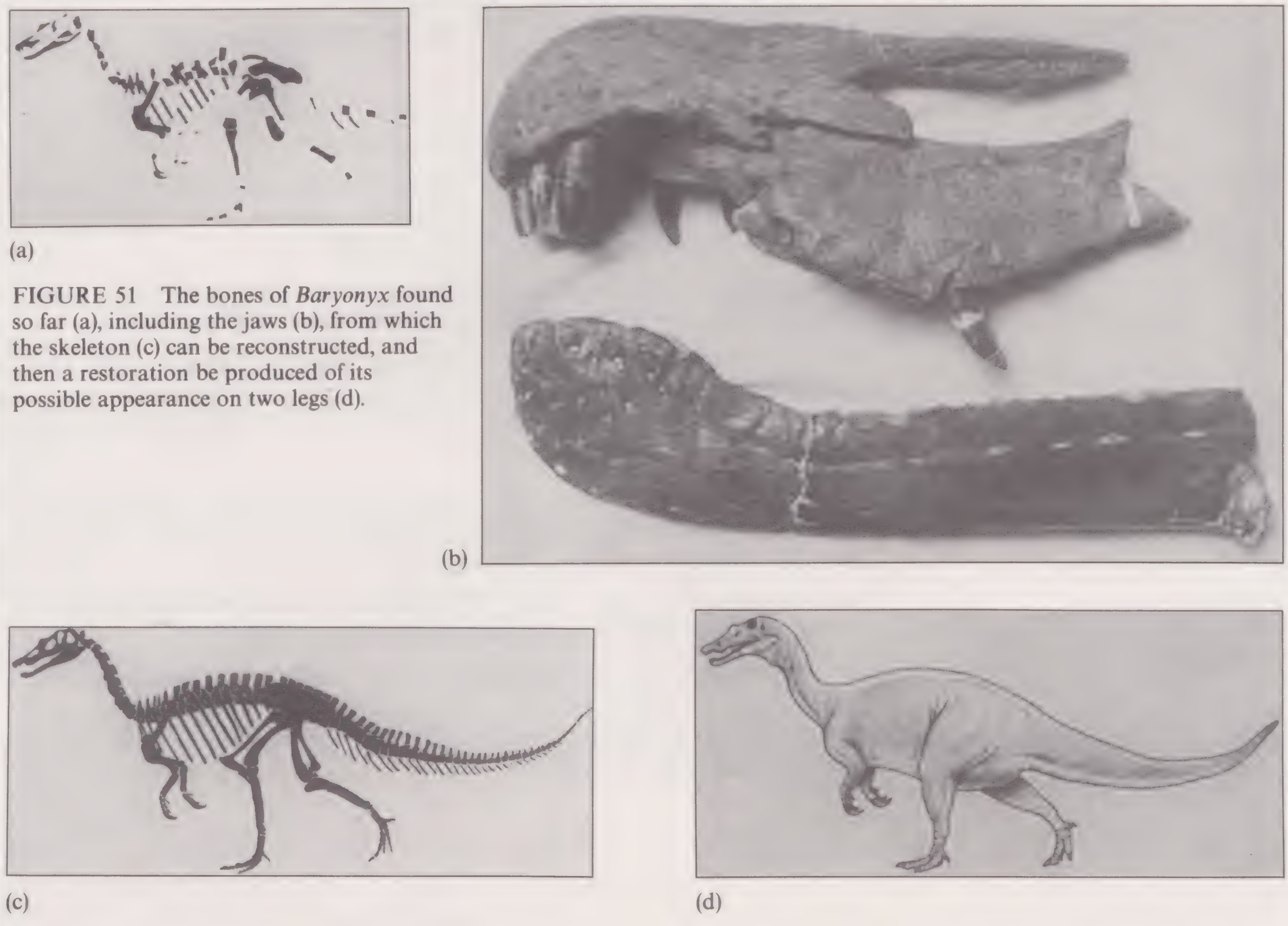


FIGURE 51 The bones of *Baryonyx* found so far (a), including the jaws (b), from which the skeleton (c) can be reconstructed, and then a restoration be produced of its possible appearance on two legs (d).

OBJECTIVES FOR UNITS 28–29

After you have worked through this double Unit, you should be able to:

1 Explain the meaning of, and use correctly, all the terms flagged in the text. (*SAQs 2, 3, 5, 6, 13–15, 17 and 18*)

2 Explain how fossils, rock types, and radiometric ages can all be used to prepare a stratigraphic column. (*SAQs 4 and 6*)

3 Using common names only, identify the fossils in the Experiment Kit and describe their habitat. (*ITQ 3, SAQ 5, AV sequences*)

4 Explain in simple terms how geological materials can be dated by radiometric methods, and be able to choose the most appropriate from several possible radiometric 'clocks' for a given dating problem. (*SAQ 8*)

5 Calculate a radiometric age from a given half-life and parent : daughter ratio for the isotopes involved in the decay scheme, using the decay equation: $t = \tau \log (N/N_0)/\log (\frac{1}{2})$ and by plotting a graph on log–linear paper. (*SAQs 9 and 10*)

6 Integrate geological data, such as radiometric dates and the relationships of rocks to each other in the field to work out their relative and absolute ages. (*SAQs 11 and 12*)

7 Identify characteristics of the Solar System that can be used to evaluate theories of its origin, particularly the distribution of planetary sizes, densities and spin periods. (*ITQ 13, SAQs 13 and 14*)

8 Explain the origin by accretional heating and selective melting processes of achondritic and iron meteorites, the Earth's mantle and core, and the layers within other terrestrial planets. (*ITQs 14 and 16, SAQ 15*)

9 Explain why carbonaceous chondrites are thought to have similar heavy-element abundances to those of the solar materials that formed some of the inner, terrestrial planets. (*ITQ 15, SAQ 15*)

10 Explain why the Earth's core, mantle, and crust could not have been formed at the same time. (*SAQ 16*)

11 Show how different sedimentary rocks reflect the carbon dioxide and oxygen content of the Earth's past atmosphere. (*SAQ 17*)

12 Account for the development of the Earth's atmosphere and ozone layer in terms of contributions from volcanic emission, photochemical dissociation and photosynthesis. (*ITQs 17–19, SAQ 18*)

13 Account for the presence of different aqueous ions in seawater, recognizing the role of volcanic and chemical weathering processes. (*ITQ 20*)

14 Describe the evolutionary sequence of life-forms throughout the Precambrian and into the Palaeozoic, indicating their probable relationship to the oxygen content of the atmosphere as deduced from the geological record. (*ITQs 21 and 22, SAQ 19*)

15 Recognize the variation in scale of climatic changes over the past 2 million years, and make quantitative estimates of the time-scales and temperature changes involved. (*ITQs 24–27*)

16 Describe the major effects of glaciation on sea-level and recognize some geological effects of glaciation. (*ITQs 26 and 28, SAQ 21*)

17 Distinguish between theories about the causes of ice ages and glaciation based on terrestrial and extraterrestrial phenomena, and recognize critical aspects of climatic change which need to be accounted for by any such theory. (*ITQs 28 and 29*)

FURTHER READING

Institute of Geological Science (1978) *Britain before Man*, (HMSO). A brief but well illustrated account of British geological history. One of a series of excellent booklets covering topics such as volcanoes, earthquakes and geological maps.

Stanley, S. M. (1985) *Earth and life through time*, W. H. Freeman and Co. This comprehensive volume covers virtually all the topics in the Earth science Units, but the emphasis is on the history of life including the diversifications of animal and plant groups, the ecosystem and mass extinctions. Beautifully illustrated.

Hutchinson, R. (1983) *The search for our beginning*, Oxford University Press. An account of planetary geochemistry, meteorites and the origin of life covering much of the material in Units 28–29, Sections 7–10, but in greater detail.

Dodd, R. T. (1981) *Thunderstones and shooting stars*, Harvard University Press. Clearly written and readable account of meteorites, their recovery and their significance.

ITQ ANSWERS AND COMMENTS

ITQ 1 Column A is pre-1900: it contains square-headed nails (6), bottles with hand-finished necks for corks (3), and soldered tin cans (1); all of these are pre-1900 materials. Column B is 1900–1920; it contains items 4, 7 and 1. Column C is 1920–1930; it contains items 2, 7 and 5.

ITQ 2 A, D, B, E, C.
A, D, B are all stone axes. A is the crudest and the most primitive, and, therefore, the oldest; D is more carefully fashioned; and B later still, being set in a handle; E, the bronze axe, comes next, before C, the iron one.

ITQ 3 (a) and (b) are brachiopods (lamp shells). Note the hole for the stalk and the bilateral symmetry of each shell, as in fossil L.

(c) and (d) are corals. (c) shows a branching colony, and (d) is a cross-section through a colony where individual branches are fused together to form a solid reef-building mass (fossil C is similar to (d)).

(e) is a crinoid (sea lily). This is a diagram of a complete animal, whereas fossil S is only the top part of a stem, cup and arms. The radial or 5-fold symmetrical arrangement of the skeleton can be better seen in Figure 5 than in fossil S.

(f) and (n) are ammonites. (f), the modern *Nautilus*, shows that all the soft parts are in the final chamber, with just a thin stalk of living tissue, the siphuncle, continuing through the old abandoned living chambers. (n) is more closely related to fossil A.

(g) and (h) are trilobites. In both cases there is a head with compound eyes, and a three-lobed segmented body and tail, as in fossil T.

(i) and (j) are gastropods. (j) is a drawing of fossil G, and (i) shows how the whole animal would appear in life. The siphon is a tube which enables the animal to get a clear current of water when 'ploughing' through the mud looking for food.

(k) and (l) are bivalves. Both of these are single shells, and clearly there is no mirror plane of symmetry through the shell (compare with fossil B and contrast with (a) and (b)).

(m) is an echinoid (sea-urchin). There is a 5-fold or radial symmetry here, as in fossil E (compare with (e) and fossil S).

ITQ 4 The unconformity represents about 60 Ma, that is, from the end of the Cretaceous (the extinction of the dinosaurs) until the appearance of hominids at about the beginning of the Quaternary Period (see the Stratigraphic Column on the back cover of this binding).

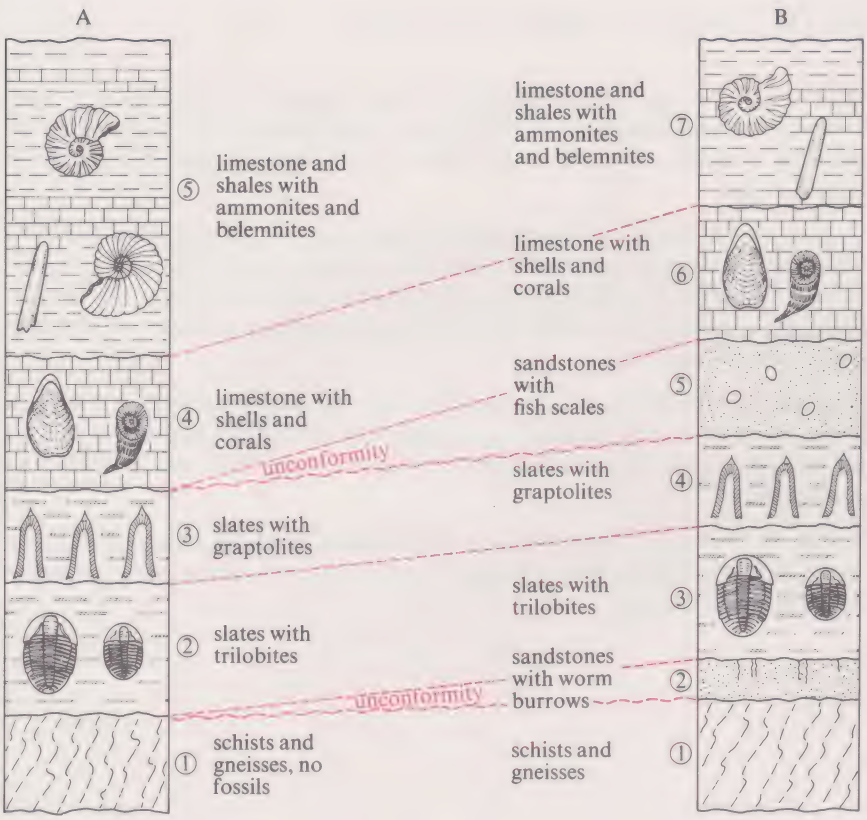


FIGURE 52 The answer to ITQ 5.

ITQ 5 (a) The beds are correlated simply by matching similar fossils: A1 = B1; A2 = B3; A3 = B4; A4 = B6; A5 = B7. See Figure 52.

(b) An unconformity must be present in column A between beds 1 and 2 since beds 1 and 3 in column B are separated by a sandstone (dotted) bed. Similarly, another unconformity between A3 and A4 is represented by another sandstone bed between B4 and B6 (see Figure 52). It is likely, therefore, that area A was above sea-level and suffered erosion twice while sandstone beds were deposited at B.

ITQ 6 From the Tertiary back to the top of the Lower Palaeozoic—that is, about the last 400 Ma. From the London Clay (Eocene) at 50 Ma back to Smith's Red and Dunstone (Devonian) at 400 Ma. (The 'Killas, or Slate and other strata' at the bottom of Smith's column are the Silurian and strata below in the modern Stratigraphic Column, but that is difficult to decide from Figures 14 and 15.)

ITQ 7 Because the half-life of the decay is too short—virtually all the activity of ${}^{14}_{6}C$ is lost long before 1 Ma, which is a very short period on the geological time-scale. In fact, useful dating is confined to the last 60 000 years. We need an isotope with a half-life comparable in length to the geological time being measured.

ITQ 8 (a) See Figure 53.

(b) After 1 hour, 50% of parent isotope remains; after 2 hours, 25% of parent isotope remains; after 3 hours, 12.5% parent isotope remains. Therefore the ratio of 1:500 (proportion of remaining parent isotope is one part in 500, or 0.2%) will be reached in 9 half-lives = 9 hours.

(c) 1:5 000 ratio (one part in 5 000 or 0.02%) will be reached in about 12.3 half-lives or 12.3 hours.

ITQ 9 1.56×10^8 atoms. The number of parent atoms remaining can be calculated for the first 6 hours as in Table 12.

Number of parent atoms left after 6 hours

$$= 10^{10} \times \tfrac{1}{64}$$

$$\approx 1.56 \times 10^8$$

Note an alternative way of working out the number of atoms remaining after six half-lives is by using Equation 1:

$$N = N_0 \times (\tfrac{1}{2})^n \qquad (1)^*$$

Therefore,

$$N = 10^{10} \times (\tfrac{1}{2})^6$$

$$= 10^{10} \times (\tfrac{1}{64})$$

$$\approx 1.56 \times 10^8$$

ITQ 10 (a) If the proportions of parent : daughter are 1:1 then the sample is exactly one half-life old, that is, 704 Ma.

(b) If the parent : daughter ratio is 1:15, the rock is exactly 4 half-lives old since $\frac{1}{16}$ of the parent nuclei survive (the other $\frac{15}{16}$ being converted into daughter nuclei—see Table 12 in the answer to ITQ 9). Therefore the age must be 4×704 Ma = 2 816 Ma.

Or, by using

$$t = \tau \log (N/N_0)/\log \tfrac{1}{2} \qquad (3)^*$$

$$t = 704 \log (\tfrac{1}{16})/\log (\tfrac{1}{2})\ \text{Ma}$$

Therefore

$$t = 2\,816\ \text{Ma}.$$

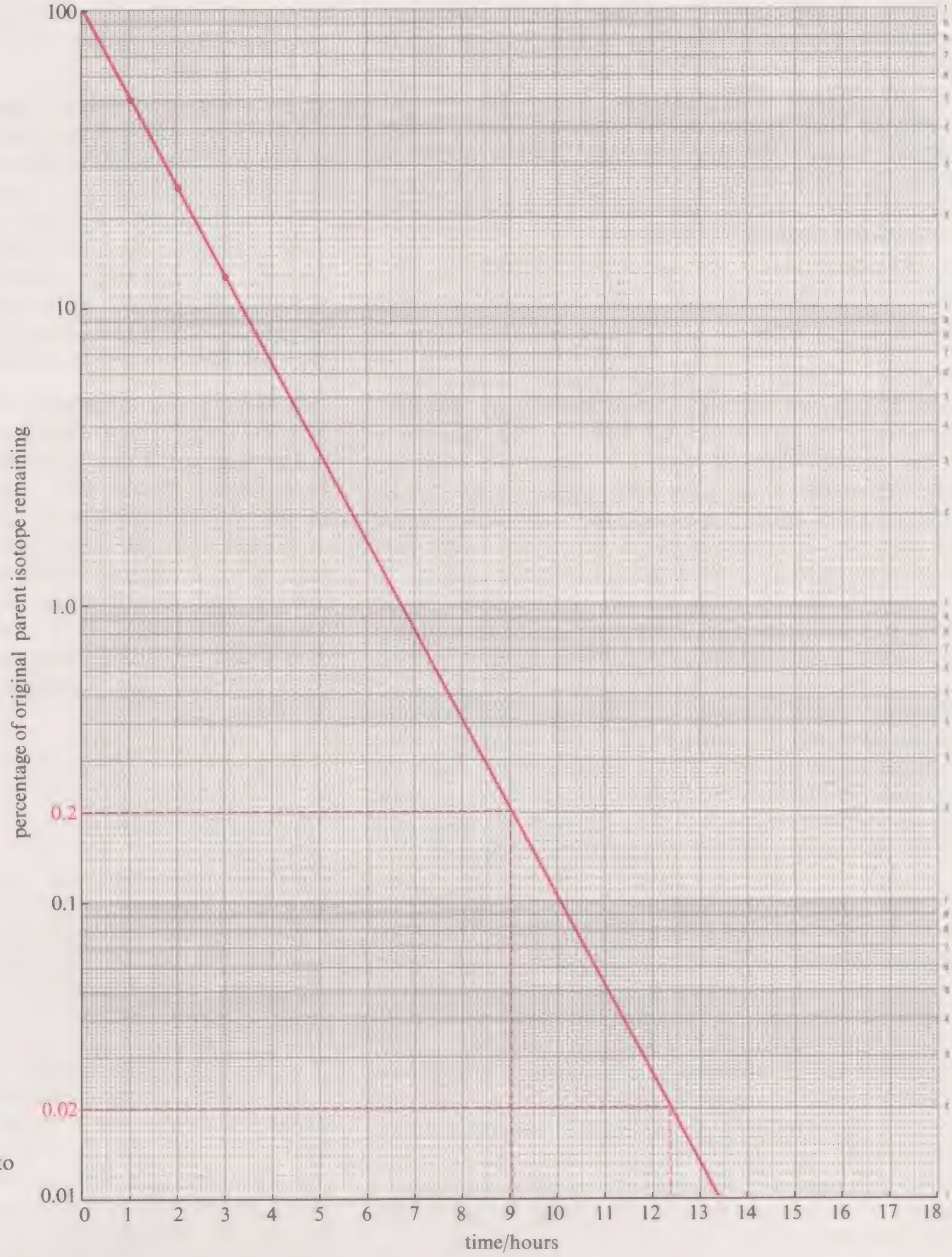


FIGURE 53 The answer to ITQ 8a.

TABLE 12 (For ITQ 9)

half-lives elapsed	0	1	2	3	4	5	6
number of parent atoms left	10^{10}	$10^{10} \times \frac{1}{2}$	$10^{10} \times \frac{1}{4}$	$10^{10} \times \frac{1}{8}$	$10^{10} \times \frac{1}{16}$	$10^{10} \times \frac{1}{32}$	$10^{10} \times \frac{1}{64}$

ITQ 11 (i) (b). A lava is identified by a single zone of contact metamorphism along its lower margin.

(ii) (a). A sill is identified by contact metamorphism along both its margins.

(iii) (c), (d) and (e). A dyke cross-cuts the strata it intrudes.

(iv) (a), (c) and (d). In (a) the igneous rock metamorphoses the top of A and the bottom of B. Therefore they must be older than the sill. In (c) and (d) the dyke cuts and metamorphoses both A and B and must therefore be younger than A and B.

(v) (b) and (e). In (b) sedimentary rock B was laid down on the lava and must therefore be younger than the lava. The contact metamorphism at the top of A shows that the lava is younger than A. In (e) the dyke is younger than A because it cuts and metamorphoses it. It is older than B because erosion occurred after the dyke was intruded and before B was laid down. (See Figure 23a.)

ITQ 12 (a) Relative age of Shap granite from fossil evidence: Maximum age, from fossils in beds cut by Shap granite, dating from the *beginning of the Silurian* Period: *440* Ma. Minimum age, from fossils in beds overlying Shap granite, dating from the *Lower Carboniferous* Period: *320* Ma. The Shap granite shown in Plate 29 is thus similar to the granite shown in Figure 23a, with the Lower Carboniferous strata of Shap being equivalent to beds B in Figure 23a.

(b) Absolute age of zircon crystals in Shap granite: 390 ± 6 Ma. Absolute age of mica crystals in Shap granite: 397 ± 4 Ma.

ITQ 13 The four inner planets (Mercury, Venus, Earth and Mars) are all small and have high densities, between 3.95 and $5.52 \times 10^3\,\mathrm{kg\,m^{-3}}$. The four large outer planets (Jupiter, Saturn, Uranus and Neptune) and the smaller Pluto have low densities, between 0.69 and $1.7 \times 10^3\,\mathrm{kg\,m^{-3}}$. Although the inner planets could all have similar compositions to that of the Earth (iron cores and silicate mantles), the outer planets are much too low in density to be similar to the Earth. Apart from this simple division, there is no simple relationship between the size of the planets and their density.

ITQ 14 The achondritic meteorites are made of peridotite, whereas the chondrites, and the stony–irons, contain dispersed iron and a framework of iron-rich material, respectively. So the achondrites are most likely to represent the mantles that surrounded the iron cores in the planets from which the materials are derived.

ITQ 15 Because the elements depleted in the Earth's crust are the ones that independent evidence (Units 5–6) suggests may go to form the Earth's mantle and, in particular, its core (note especially the depletion of Ni in the crust), and that the enriched ones are important in crust-forming materials, the Earth as a whole may well be 'chondritic'. Notice that iron is common in both core and crust; iron concentrates into the primary melts that form in the mantle which go to make oceanic and then continental crust (see Unit 27, Sections 3.3 and 3.6), whereas magnesium silicates require much higher temperatures to become molten, and remain in the mantle as peridotites.

ITQ 16 The magnitude of the force exerted on a particle (mass m) towards a growing planet (mass M) is given by:

$$F = GmM/d^2$$

where d is the distance between the centre of m and the centre of M (see Unit 3, Section 6.1). Since M is increasing, so does F, as indicated in the text. But you also know that $F = ma$, so as F increases, the acceleration (a) of a given accreting particle (mass m), also increases. Consequently, impact velocities (v) must increase with increasing planetary size and so too do kinetic energies $(\frac{1}{2})mv^2$. On impact, energy must be conserved and, in addition to accelerating the forming planet, much of the energy must be converted into heat. Accretion of planets is therefore accompanied by heating.

ITQ 17 (a) Photosynthesis involves the formation of carbohydrates and O_2 from H_2O and CO_2. So once these organisms became widely established, their continued distribution in the oceans would cause oxygen levels to increase.

(b) As oxygen is liberated, some of it is converted into ozone in the upper atmosphere ($3O_2 \longrightarrow 2O_3$). The existence of this ozone is important, because it absorbs some of the harmful u.v. radiation which would otherwise reach the surface of the Earth. Living organisms need protection from this radiation, which is harmful because it breaks down cellular DNA. Thus, the progressive development of the ozone layer would reduce the amount of this radiation at the surface and allow the evolution of complex organisms to occur.

ITQ 18 Oxygen. Excluding the water-soluble SO_2, SO_3, F_2 and Cl_2 from the volcanic gas list, you should realize that of the four important atmospheric gases in Table 10, N_2, Ar and CO_2 are all present in the volcanic list but in different proportions to their atmospheric proportions. The most important absence from the volcanic gases is oxygen. This is because oxygen is highly reactive, and, if present, would be used up in making oxides such as SO_2, CO_2 and H_2O. Remember also that iron(II) in igneous magmas would also react with any available oxygen. Therefore, no free oxygen is found in volcanic gases.

ITQ 19 In no small way, the evolutionary opportunity for land plants and animals to develop was created by the build-up of atmospheric oxygen, which in turn allowed the ozone layer to become a more effective shield. As you should recall from ITQ 17, conditions on land up to this time were hostile to life because of the toxic levels of u.v. radiation. So early organisms required the relative shelter of ocean waters, which absorb the toxic radiation. We shall take up this point again in Section 10.4.

ITQ 20 It is almost certain that, together with water itself, chlorine, sulphur dioxide, bromine and carbon dioxide enter seawater from the atmosphere after having been emitted as volcanic gases. You should remember from the discussion at the end of Section 9.3 that it is just these four important constituents of volcanic gases (Table 10) which do not feature, except for small quantities of CO_2, in the present-day atmosphere.

ITQ 21 The Precambrian fossil animal record is sparse because the known Precambrian animal fossils are all soft-bodied impressions, which suggests that Precambrian animals had not developed hard parts. As soft organic tissues decay rapidly after death, the chances of preservation are much less likely than for the remains of subsequently evolved animals with hard shells or skeletons. We also know that the rapid evolution of organisms did not become possible until the development of eukaryotic cells between 1 000 and 1 600 Ma ago, and the evolution of metazoan life apparently followed this step at about 700 Ma ago.

ITQ 22 (a) The vast development of metazoan life is related to greatly increased levels of atmospheric oxygen, so the balance between photosynthetic and respiratory organisms must have been changing to produce an ever-increasing amount of free oxygen.

(b) This in turn would have lead to a more efficient ozone layer, enabling organisms to expand into progressively shallower water environments which formerly had been subject to harmful levels of u.v. radiation.

ITQ 23 It is likely that additional photosynthesis would have led to an increase in the oxygen level of the atmosphere. Also, protection afforded by the plants would have provided additional ecological niches for animals on land.

ITQ 24 These peat and lake deposits contain abundant organic material. The half-life of $^{14}_{6}C$ is 5 700 years, so carbon dating could be used. If you are still uncertain about the principles of radiometric dating, re-read Section 4.

ITQ 25

	Winter/°C	Summer/°C
(a)	3.5–4.0	15.6–15.8
(b)	3.2–4.2	15.4–16.7
(c)	3.2–5.1	15.4–17.5

As you can see, the longer the period we examine, the greater the temperature ranges involved.

ITQ 26 No. The two methods you have met for dating lake sediments are counting annual varves (Section 2.3) and radiocarbon dating of organic remains (Section 4). Varves are laid down in front of ice-sheets, particularly melting ice-sheets, so this record cannot extend back before the last growth of the ice. Carbon dating has a similarly restricted usefulness. Interglacial lake deposits are likely to be over 50 000 years old and probably much older still. So many half-lives of $^{14}_{6}C$ will have elapsed that there will be very little radioactive material left in the sample, and it will not be possible to measure the decay rates of this residual fraction against the normal background of radioactivity. Such deposits can only be related to the Stratigraphic Column by correlation with fossils.

ITQ 27 By summing the width of the peaks in Figure 47 that rise above the present-day temperature line, the percentage of the last 400×10^3 years that had a climate as warm as or warmer than that of today can be estimated at 10–20%. This means that we live in a relatively warm part of the Quaternary Ice Age. No further complaints about the weather, please!

ITQ 28 (a) Eustatic changes in sea-level are world-wide and affect all coasts since they result from the change in the volume of water available world-wide. (Figure 54a).

(b) Isostatic effects are found principally in areas that are heavily glaciated since they result from the depression of land-masses due to the mass of the ice-sheet. (Figure 54b). The two trends do not reinforce but oppose each other, leaving a smaller net effect. During glacial times, sea-level falls eustatically (by about 120 m during the last glaciation; see Figure 54a). The land levels in the most heavily glaciated areas are also pressed down, often by even greater amounts, because of the ice-load (Figure 54b).

ITQ 29 Ice, having a white surface, will increase the reflectiveness of the Earth's surface. Thus, more of the incoming radiation will be reflected back into space and less heat will be absorbed and be available to melt the ice. Once ice cover is established, conditions become even more favourable for it to persist.

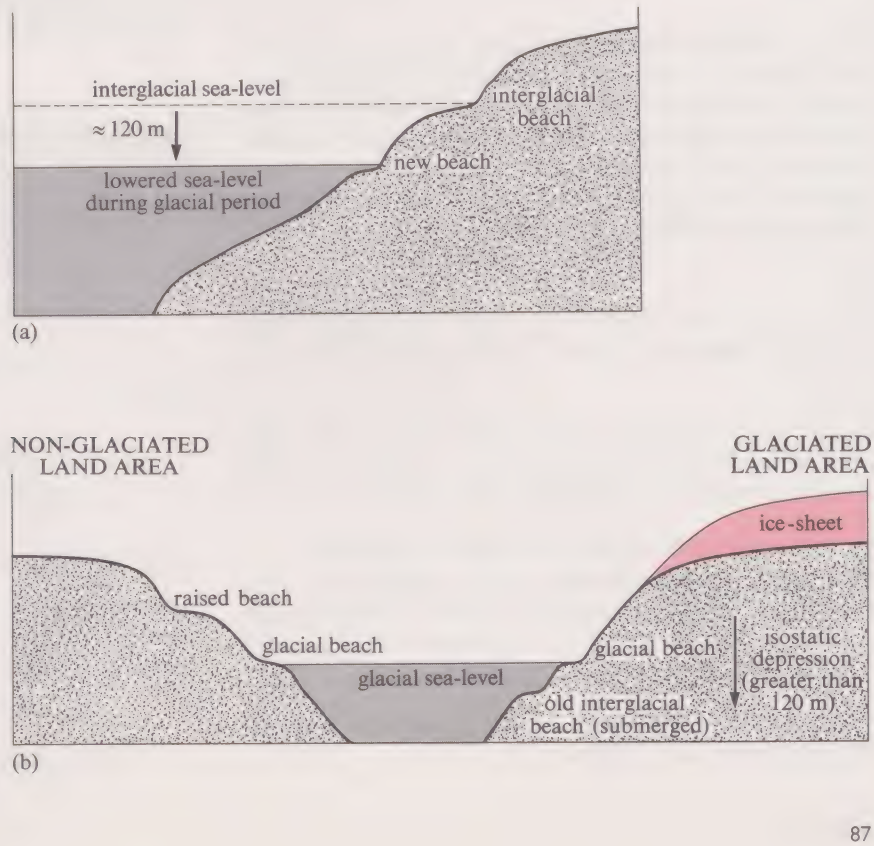


FIGURE 54 During a glacial period there is (a) a world-wide eustatic fall in sea-level, but (b) glaciated land-masses sink by isostatic adjustment beneath their ice-load. On the right of part (b) a heavily glaciated area is shown to sink more than the eustatic fall. The pattern of glacial and interglacial beaches therefore becomes complex and depends on the relative ice-load of any land-mass. (ITQ 28.)

SAQ ANSWERS AND COMMENTS

SAQ 1 (a) 0.23 s. This is calculated as follows:
If 4 600 Ma corresponds to 3 hours, then 1 Ma corresponds to

$$\frac{3}{4.6 \times 10^3} \text{ hours}$$

and 100 000 years ($= 10^{-1}$ Ma) corresponds to

$$\frac{3}{4.6 \times 10^3} \times 10^{-1} \text{ hours}$$

But 1 hour = 3 600 seconds, so 100 000 years corresponds to

$$\frac{3 \times 3600}{4.6 \times 10^3} \times 10^{-1} \text{ seconds}$$

$$\approx 0.23\text{ s}$$

(b) 1.15×10^{-2} s

If 100 000 years correspond to 0.23 s, then 5 000 years correspond to

$$\frac{0.23 \times 5}{100} \text{ seconds}$$

$$\approx 1.15 \times 10^{-2}\text{ s.}$$

So civilization would appear about a hundredth of a second from the end; it might just get on the very last frame of the film!

SAQ 2 (a) S1, S5, S6, S7, S8, S9 are Palaeozoic; S4 and S10 are Mesozoic; S2 and S3 are Cainozoic.

(b) S1 Permian; S2 Tertiary; S3 Tertiary; S4 Cretaceous; S5 Silurian; S6 Carboniferous, S7 Carboniferous; S8 Devonian; S9 Ordovician; S10 Cretaceous.

SAQ 3 Graded bedding that has coarser sediment at the bottom of each unit, gradually becoming finer-grained towards the top, is interpreted as representing the gradual transition from rapid deposition of coarse sediment during the summer, to deposition of the finer suspended clay particles during the winter, when no sediment was coming into the lake.

SAQ 4 (a) See Figure 55. (The correlation lines between distinctive marker horizons are shown as dashed.)

(b) See Figure 55. (The stratigraphic column for these beds is made by 'stacking' up all the beds in chronological order, with the oldest at the bottom.)

(c) The oldest beds are at the bottom of column E.

Note bed b.c. easily correlates across columns B, C and D. The pair of thick beds at the top of E correlates with those near the bottom of C. The beds at the top of B correlate with those at the bottom of A.

(d) 158 years, as shown in the stratigraphic column on the right-hand side of Figure 55.

SAQ 5 (a) There are two more or less equal shells to the oyster, and each shell is certainly not bilaterally symmetrical, therefore it is a bivalve, like fossil B.

(b) The garden snail inhabits a spirally coiled shell, and therefore it is a gastropod, like fossil G.

(c) The edible clam is a bivalve, though you may have wondered about this because the shells are nearly bilaterally symmetrical.

(d) The periwinkle inhabits a spirally coiled shell, and therefore it is a gastropod, like fossil G.

(e) Starfish have 5-fold symmetry, and are therefore related to the echinoid, fossil E, and the crinoid, fossil S.

SAQ 6 Neither. Smith applied the faunal succession as a way of correlating rock strata to help him make a geological map. He could have interpreted the faunal succession in either a catastrophist way (Cuvier) or in a uniformitarianist way (Darwin).

SAQ 7 (b). If there is only one type of rock present, it would be difficult to use rock-stratigraphic units or beds (a). You would also be unable to define time periods without radiometric ages (c). You would, therefore, divide the column into biostratigraphic units, or zones, by the fossils (b).

SAQ 8 ${}^{235}_{92}\text{U} \longrightarrow {}^{207}_{82}\text{Pb}$, with its faster decay rate. Between 500 Ma ago and the present there has been considerable change in the proportion of ${}^{235}_{92}\text{U}$ to ${}^{207}_{82}\text{Pb}$. With its slower decay rate, ${}^{238}_{92}\text{U}$ has decayed less in the last 500 Ma, so it should provide less reliable dates.

SAQ 9 $t \approx 3090$ Ma. There are two ways of working this out:

(a) by calculation:

Parent: daughter ratio = 1 : 20, $N = 1$ and $N_0 = 21$.

$\tau = 704$ Ma (from Table 6)

$$t = \tau \log (N/N_0)/\log (\tfrac{1}{2}) \qquad (3)^*$$

Therefore,

$$t = 704 \log (\tfrac{1}{21})/\log (\tfrac{1}{2}) \text{ Ma}$$

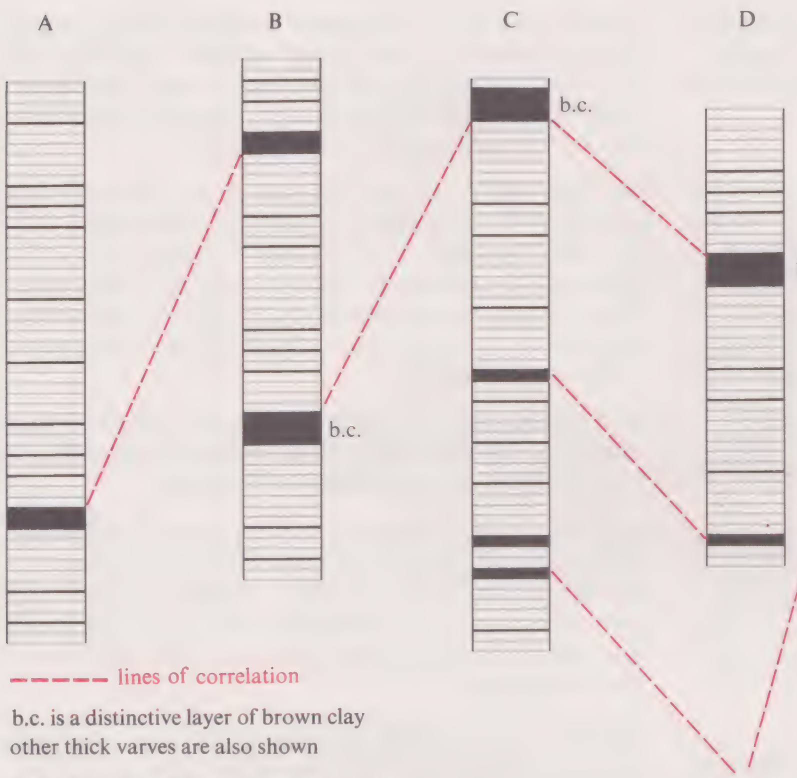
$$t \approx 3090 \text{ Ma.}$$

(b) graphically, using Figure 53 (see answer to ITQ 8):

The parent : daughter ratio is 1 : 20, therefore only 5% of the original parent is left. This will happen after about 4.4 half-lives (from Figure 53).

$$t \approx 4.4 \times 704 \text{ Ma}$$

$$t \approx 3100 \text{ Ma}$$



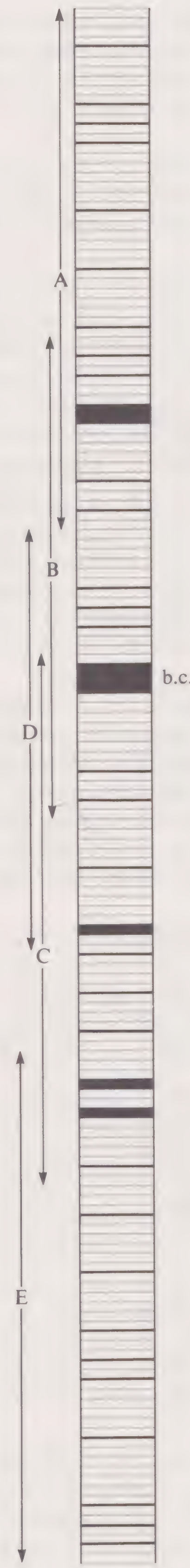


FIGURE 55 The answer to SAQ 4.

SAQ 10 $t \approx 2\,440$ Ma. There are two ways in which you could have arrived at the correct answer:

(a) by calculation:
Only half of the daughter (lead) atoms result from decay, so the parent : daughter ratio = 1 : 10, $N = 1$ and $N_0 = 11$.

$$\tau = 704\ \text{Ma}$$

$$t = \tau \log (N/N_0)/\log (\tfrac{1}{2}) \qquad (3)^*$$

$$t = 704 \log (\tfrac{1}{11})/\log (\tfrac{1}{2})\ \text{Ma}$$

Therefore $t \approx 2\,440$ Ma

(b) graphically, using Figure 52:
The parent : daughter ratio is 1 : 10 therefore 10% of the original parent is left. This will happen after about 3.4 half-lives (from Figure 52).

$$t \approx 3.4 \times 704\ \text{Ma}$$

$$t \approx 2\,400\ \text{Ma}$$

SAQ 11 (a) A–E is the older sedimentary series, below the unconformity at the base of F. F–H^2 is the younger series above the unconformity.

(b) J is the older, because it was eroded before the second sedimentary series was laid down.

(c) The seqence is: A–E, the first sedimentary series; intrusion of dyke, J; F–H^2, the second sedimentary series; intrusion of sill, I.

(d) An unconformity or old erosion surface.

(e) Yes. If rock I were a lava flow, not a sill, then it would represent a break in sedimentation between H^1 and H^2, and so be older than H^2.

SAQ 12 (a) Younger. The granite cuts across the strata A–D, and these sediments have all been metamorphosed when they come in contact with the granite.

(b) Older. There is no evidence of metamorphism and there are pebbles of granite in the overlying sediments. The upper surface of the granite is therefore a major unconformity. The granite must originally have been intruded into crustal rocks which have been eroded away.

Erosion removed these rocks and cut into the granite, to leave a huge granite hill. Sediments X and Y accumulated against the sides, and finally Z completely covered the granite.

SAQ 13 All are correct except B, which is true of the inner planets. The outer planets are light and essentially gaseous with major amounts of hydrogen and helium.

SAQ 14 (a) As planetary rings of material are left in stable orbit around the contracting centre (the Sun), the nebular theory predicts that the latter should spin much more rapidly than the planets. The fact that the Sun spins much more slowly than the outer planets, in particular, has caused severe problems for this theory during its history.

(b) The close interaction between two stars, as conceived by Jeans and Jeffreys, produced a hot filament of solar material, which, it was argued, was unable to condense to form planets but rather would disperse. The other difficulty was the unlikely statistical chance of the necessary close encounter between two stars.

SAQ 15 A, B and E are correct. C is false because chondrules are thought to be an original feature of chondrite development during 'nebula' condensation: they are destroyed, not produced, by metamorphism. D is false because the chondritic Earth model says that the composition of the whole Earth, not just its core, is akin to certain chondrites.

SAQ 16 (a) The core was developed on a short time-scale (10^6 to 10^8 years) as a result of partial melting near the surface, caused principally by accretional kinetic energy release. A liquid rich in iron and sulphur sank towards the Earth's centre and formed the core.

(b) Core–mantle separation also took place over a period of 10^6 to 10^8 years: the higher-melting peridotite mantle was left after the denser iron-rich melt sank into the core. (However, the mantle has since evolved in a different way on a long time-scale owing to the extraction of crust by partial melting.)

(c) The crust has been produced over the whole of the Earth's history as a result of volcanic processes driven by mantle convection (Units 7–8). The heat source for this convection is the decay of long-lived radioactive isotopes in the mantle.

SAQ 17 B, D and G. B is false because detrital pyrite is stable only in reducing, not oxidizing environments. D is false because limestone was precipitated from seawater mainly in the last 2×10^3 Ma (see Figure 36), before which CO_2 remained in the atmosphere or dissolved in seawater. Coal formation had to await the evolution of land plants and has only characterized the last 400 Ma. G is false because meteoric water has nothing to do with meteorites, but is, in fact, rainwater that has become trapped in pore spaces of rocks to become groundwater.

SAQ 18 (a) Processes (iv), (vii) and (ix) increase the carbon dioxide content of the atmosphere. (iv) involves the burning of hydrocarbons in oxygen. For (vii) see Tables 9 and 10 for a comparison between CO_2 concentration present in gases from volcanic emissions and CO_2 concentration in the atmosphere. (ix), the respiration of land animals that breathe oxygen, is accompanied by CO_2 exhalation.

(b) Processes (i), (ii), and (v) decrease the carbon dioxide content of the atmosphere. (i) and (v) both remove CO_2 by photosynthesis and release oxygen. (ii) is a hydrosphere–atmosphere interaction in that the precipitation of more limestone reduces the HCO_3^- content of seawater and causes more CO_2 gas in the atmosphere to become dissolved.

(c) Processes (iii), (vi) and (viii) leave the carbon dioxide content of the atmosphere unchanged, although (iii) and (vi) both affect the concentration of oxygen.

SAQ 19 A, (i) (Figure 6); B, (iv) (Section 10.3 and Figure 36); C, (v) (Section 10.3); D, (vii) (Sections 9.2 and 10.3); E, (vi) (Section 10.3); F, (viii) (Section 10.2 and Figure 36); G, (ix) (Section 10.3); H, (ii) (Sections 9.4 and 10.4); I, (iii) (Section 10.4); J, (vi) (Section 9.1 and Figure 36).

SAQ 20 All are correct except B. Eustatic sea-level changes are produced instantaneously after glaciations as the ice melts and the water volume of the oceans increases. The land surface rises isostatically on a rather longer time-scale.

SAQ 21 Figure 50a, which is from a site in the Mediterranean, represents a steady rise of sea-level over the past 15 000 years, which accelerated in the period 9 000 to 6 000 years ago. The principal component of the sea-level change must be eustatic, and therefore the area has not been glaciated. No isostatic depression and recovery is recorded.

Figure 50b shows sea-levels that, over much of the past 15 000 years, were higher than the present elevation of sea-level in that area. This can only mean that the land has undergone considerable isostatic uplift during this time and was depressed by a cover of glacier ice at the maximum of the last glaciation 18 000 years ago. Consequently, the curve records the combined effects of isostatic recovery of the land (taking place at an ever decreasing rate after unloading) and the eustatic rise in sea-level (which has the opposite effect, see Figure 50a). We might anticipate that the eustatic change outpaced the isostatic change when the ice first started to melt over 15 000 years ago. But the pattern of Figure 50b is complicated by a further eustatic change in the period 9 000 to 6 000 years ago.

Don't worry if you were unable to explain this 'hump' in Figure 50b. It is there because the area concerned lay to the edge of the ice-sheets in north-west Scotland (Figure 46), with the result that it became unloaded and recovered isostatically when the ice-sheets started to shrink slowly (Figure 50a). This recovery was well advanced when the major melting/eustatic sea-level rises took place between 9 000 and 6 000 years ago. For this short period, the post-glacial, eustatic rise in sea-level exceeded the isostatic rise in land level. During the last 6 000 years the ice-sheets have melted a little more, approaching their present limits. Little further eustatic rise in sea-level has taken place, but isostatic rise of former glaciated areas has continued rather slowly.

INDEX FOR UNITS 28–29

ACKNOWLEDGEMENTS

Grateful acknowledgement is made to the following sources for material used in this double Unit:

Figure 16 BBC Hulton Picture Library, from a block in the possession of the Edinburgh Geological Society; *Figure 17(a)* G. C. Brown; *Figure 17(b)* I. G. Gass; *Figure 18* British Geological Survey; *Figures 30 and 31(a, b and c)* photos distributed by the Smithsonian Institute; *Figures 34 and 51* by permission of the British Museum (Natural History); *Figure 35* Aerofilms Ltd.; *Figure 37* Prentice-Hall; *Figure 38(a and b)* Preston Cloud, Santa Barbara.

Plates 21, 22(a), 24(b), 25 and 26 Seaphot Ltd.: Planet Earth Pictures; *Plates 22(b), 23 and 24(a)* Biofotos/Heather Angel; *Plates 30 and 31* British Museum (Natural History) Geological Museum, London.

PLATE 21 Edible periwinkle, *Littorina littorea*. This is a small marine gastropod with fewer coils than fossil G in the Experiment Kit.

PLATE 22a Slate Pencil sea urchin, *Heterocentrotus mammillatus*. The huge spines here are probably much bigger than the spines possessed by fossil E in the Kit when alive.

PLATE 22b Edible sea urchin, *Echinus esculentus*. For use with assessment material.

PLATE 23 Lampshells, *Macandrevia cranium*. These present-day brachiopods are shown attached by their stalks to stones in a Norwegian fjord, and are much smaller than fossil L in the Kit.

PLATE 24a Cockle, *Laevicardium crassum*, showing the foot (right) and siphon (left) emerging from valves which are mirror images of each other. These soft parts would be at the base of fossil B in the Kit.

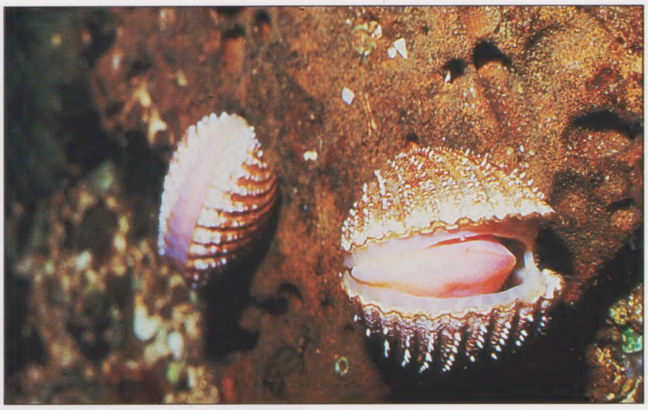


PLATE 24b Prickly cockle, *Cardium echinatum*. For use with assessment material.

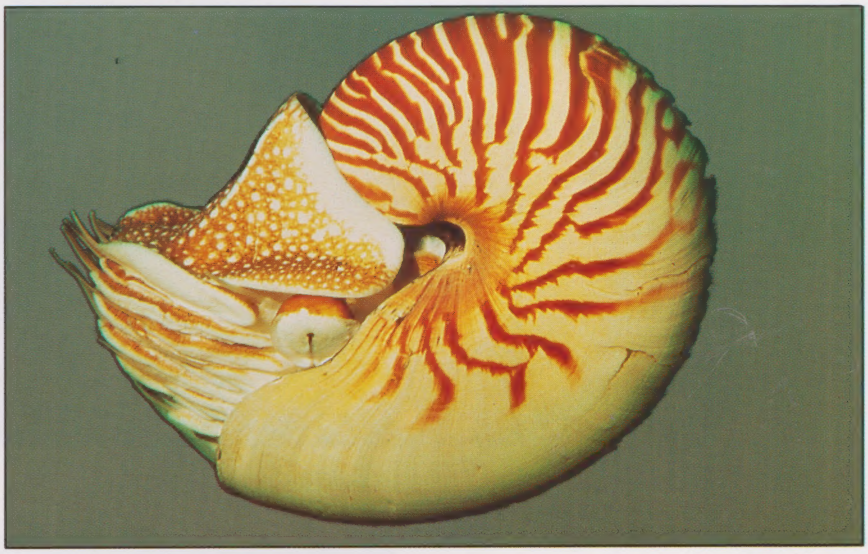


PLATE 25 Modern nautilus, *Nautilus reperius*. The tentacles, eye and other soft parts of this squid-like animal can be seen on the left, projecting from the opening of the coiled shell. The earlier coils of the animal are concealed by the last coil. (Compare this photograph with fossil A in the Kit.)

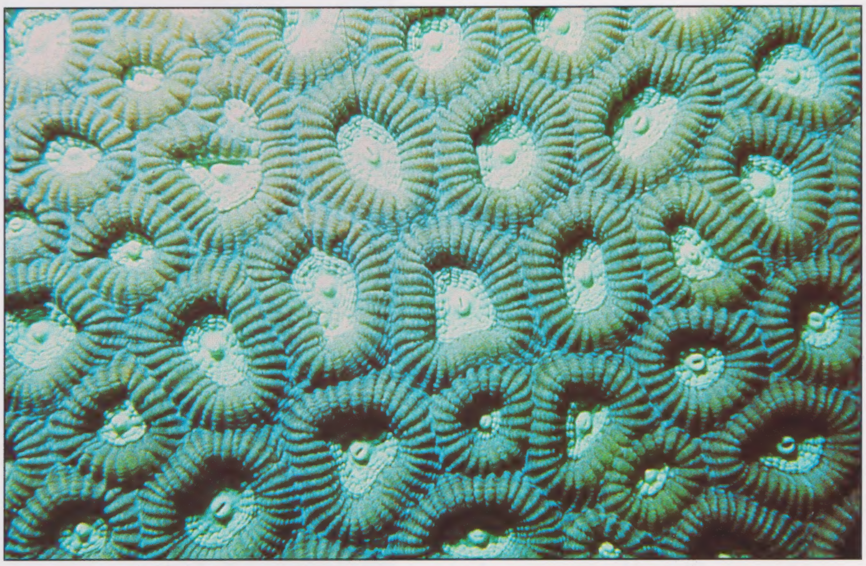


PLATE 26 Modern compound coral, *Favia sp.* Part of a large colony where the corallites grow together as in fossil C in the Kit.

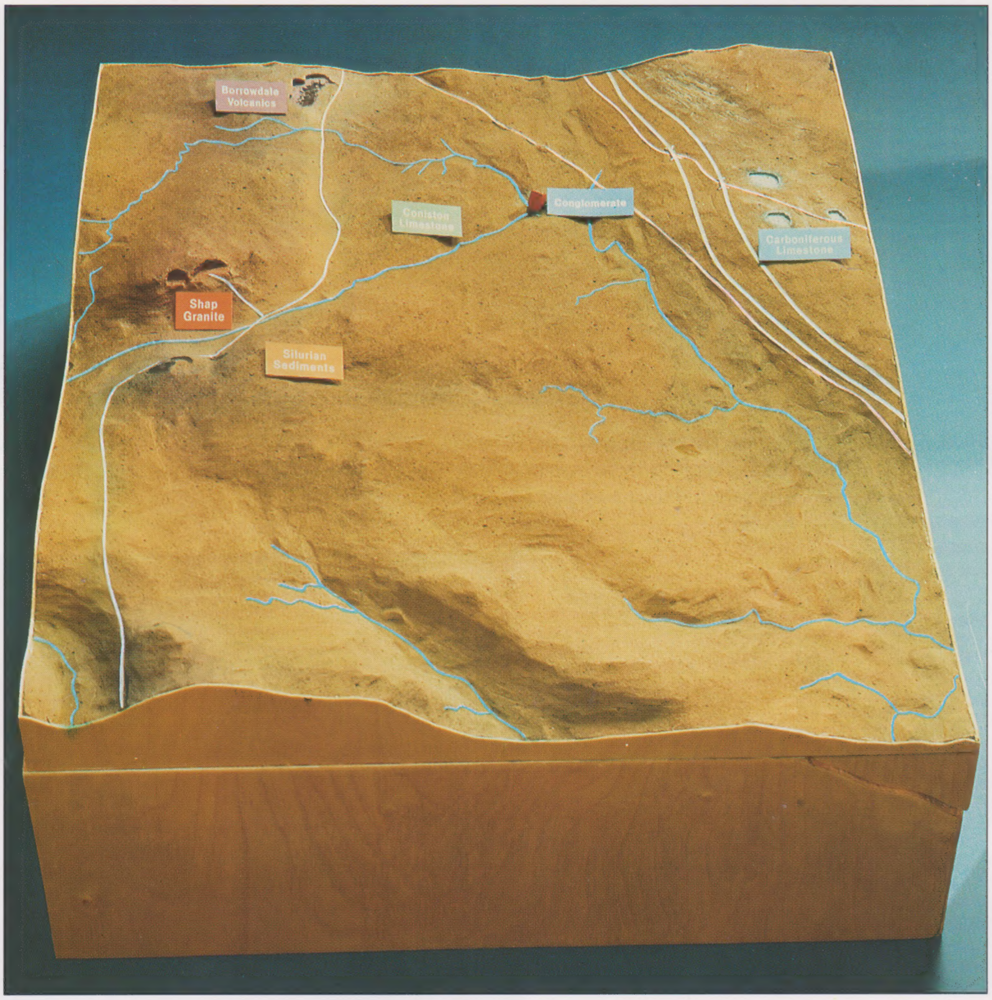


PLATE 27 Model of Shap area looking north to show localities in the TV programme 'Dating a granite'. The Shap Wells Hotel (shown as a Monopoly hotel in the photograph) lies about midway between the separated carriageways of the M6 (top right) and the A6 which passes the quarries (left).

PLATE 28 Underlying geology of area shown in Plate 27 with top surface removed. Carboniferous strata have been partially removed to show the unconformity surface/old erosion surface.

PLATE 29 Model of Rockhope borehole: illustrating the junction between granite and Carboniferous Limestone. The top of the granite is weathered and cracked, and there are granite pebbles in the basal beds of limestone.

PLATE 30 Shallow tropical seas of Welsh borderlands about 425 Ma ago. Fixed crinoids and corals are abundant, with some crawling gastropods and trilobites, with some swimming shells also.

PLATE 31 Vertebrate life in the shallow seas and around the Jurassic shores about 150 Ma ago.

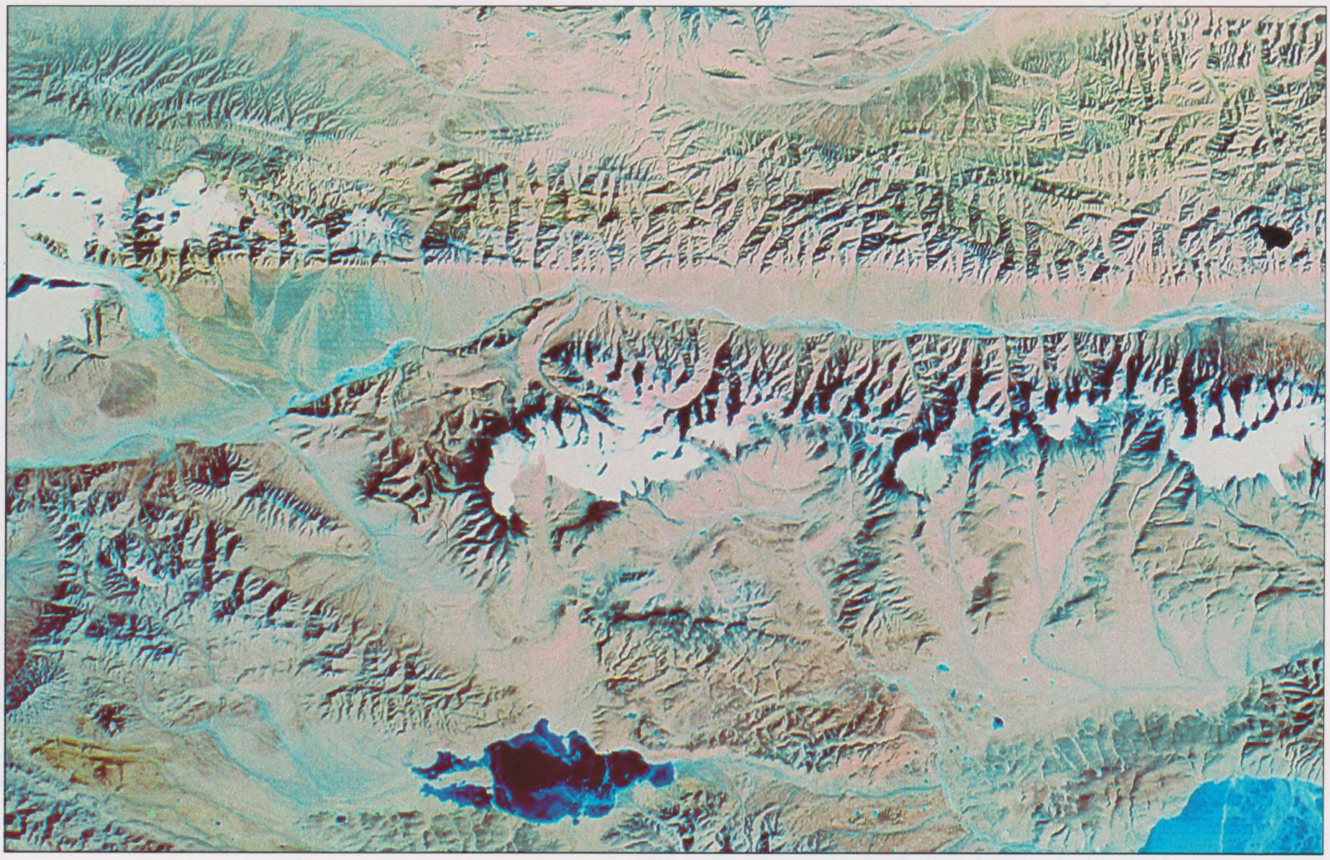


PLATE 32 Landsat Multispectral Scanner image from the Kunlun Mountains of northern Tibet. The sharp east–west feature in the top half of the image records a recent fault with horizontal movement. South of the fault, two circular volcanic calderas can be seen with a dark lava field further south. Colours are false, but white areas indicate glaciers and blue areas indicate lakes.